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Wireless Sensor Review

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March 2001

Final Report for the period May 2000 to March 2001

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NOTICES

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This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

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The goal of this study was to investigate wireless sensor products and technologies for use in the prediction of component failure for legacy aircraft. Further, the study was to rank the identified products and technologies and select those that held the most promise for the intended maintenance task. Finally, based on the selected subset, demonstrations were to be arranged either at the vendor site, at Arthur D. Little (ADL), or at the Air Force Research Laboratory (AFRL). The commercial systems that were identified to be most applicable to aircraft maintenance were the WINS system from Sensoria, the CrossNet from Crossbow Technologies, the ATI rotating sensor system, and the CSI line of machine diagnostics products. Demonstrations were arranged for all but the CSI systems. The technology identified to be most applicable to aircraft maintenance included three patents from Raytheon and one from The Aerospace Corporation. Raytheon has subsequently sold the rights to one of the patents to CBL Systems. The remaining two are still held by Raytheon. The Aerospace Corporation patent is available royalty free to the Air Force, since it was developed under government funding.

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1. Executive Summary

1.1 Overview

The goal of this study was to investigate wireless sensor products and technologies for use in the prediction of component failure for legacy aircraft. Further, the study was to rank the identified products and technologies and select those that held the most promise for the intended maintenance task. Finally, based on the selected subset, demonstrations were to be arranged either at the vendor site, at Arthur D. Little (ADL), or at the Air Force Research Laboratory (AFRL).

The work started with a comprehensive search of the Internet, patent literature, and industry and NASA sources. In addition, we held one brainstorming session at ADL to be sure that we had incorporated as wide a range of ideas as possible. To evaluate the identified products and technologies, ADL used a quantitative ranking methodology based on Quality Function Deployment (QFD).

The commercial systems that were identified to be most applicable to aircraft maintenance were the WINS system from Sensoria, the CrossNet from Crossbow Technologies, the ATI rotating sensor system, and the CSI line of machine diagnostics products. Demonstrations were arranged for all but the CSI systems.

The technology identified to be most applicable to aircraft maintenance included three patents from Raytheon and one from The Aerospace Corporation. Raytheon has subsequently sold the rights to one of the patents to CBL Systems. The remaining two are still held by Raytheon. The Aerospace Corporation patent is available royalty free to the Air Force, since it was developed under government funding.

1.2 Findings

Technically viable wireless sensor and sensor systems are currently available in the marketplace. These systems are sufficiently mature to begin serious application specific design and development for the Air Force maintenance systems. The challenge will be to focus the design efforts on integrating these sensors with existing maintenance activity infrastructure in such a way as to maximize effectiveness of available maintenance resources and assets. This task will require identification of targeted user needs prior to embarking on a comprehensive system design.

1.3 Recommendations

ADL recommends that the AFRL commission a multi-pronged effort focused on leveraging the growing capability offered through wireless sensors. The recommended tasks and their objectives are as follows:

- Commission a study to identify specific maintenance needs that are not currently being met and determine the value of meeting the stated maintenance requirements.

- Develop a system architecture and design to meet the identified needs through use of available sensors, algorithms, etc. and demonstrate feasibility of the system in a laboratory test.

- Select a suitable pilot study for prototype system implementation in actual aircraft with ground support systems. The pilot study should be sufficiently limited in scale to keep costs at reasonable levels but sufficiently large in scale to demonstrate the utility of the approach. Presuming success of the pilot study, follow on activities would be required to evaluate the cost/benefit of such a system and to plan wider scale system implementation.

2. Impact Of Flight Line Maintenance Environment On Sensor Applicability

2.1 Design Implications to Survive the Air Force Environment

2.1.1 The Operational Air Force Environment

The operational Air Force environment is characterized by extreme variations, even when focusing on a specific type of aircraft, or Mission Design Series (MDS). For example, the environment in which the F-16 operates varies from the Arctic tundra region of the interior of Alaska to the desert environment of Phoenix, Arizona to the incredibly humid, swamp like environment of Valdosta, Georgia. Each of these locations is a peacetime operating location and it is conceivable that aircraft from these locations must deploy to and operate from another location dramatically different from their home base environment. Such is the case when F-16s from Fairbanks, Alaska deploy to Southeast Asia. Air Force aircraft must not only be able to operate in a variety of challenging environments, they must be able to transition from one extreme environment to another with very little preparation. Consequently, Air Force aircraft systems must operate effectively given a broad spectrum of environmental variations.

Air Force aircraft maintenance is largely an outdoor effort. Even during peacetime operations from home station, hangar space is at a premium and is usually reserved for scheduled maintenance and specific maintenance activities that require a controlled environment, such as aircraft fuel cell maintenance or painting operations. During contingency operations, the issue of scarce hangar space is even more severe. In many instances, operations are conducted from an *open ramp*, an area of open, clear tarmac. As such, internal components are routinely exposed to the external environment that may consist of rain, blowing snow, sand, mud or some combination of these elements. Whenever possible aircraft sensor design should encompass measures to mitigate the damage resulting from routine exposure to harsh external environments resulting from maintenance actions.

With the transition of the Air Force to an expeditionary aerospace force, much emphasis has been placed upon developing operational and logistics paradigms and processes that are *light and lean*[1]. Specifically, there is a major effort underway in the Air Force logistics community, called Agile Combat Support (ACS), to examine the entire Air Force logistics support system and reengineer existing methods and infrastructure to support the highly mobile, rapidly deployable posture of today's Air Force. The Air Expeditionary Force (AEF) concept represents many significant logistics challenges. One major challenge of the concept of light and lean is that units are deploying with less equipment and, due to the expeditionary nature of the operation, they are deploying to austere locations. Forward deployed maintenance personnel are faced with the challenge of less equipment and personnel to perform maintenance combined with minimal infrastructure and in-place support. Aircraft sensors that are less sensitive to

[1] Light and lean, in general, means that retaining the same combat capability while reducing the amount of equipment and personnel required to support it. Also, it implies a more rapid arrival at full operational capability when deployed with the understanding that the sustainment timeframe without resupply is much shorter, down from 30 days to 7 days typically.

these issues are a must. Sensors should be tolerant of dirty or highly variable external power supplies, and require little or no special tooling or environmental control to perform maintenance.

Another factor that characterizes the Air Force aircraft maintenance environment is the lack of experienced maintenance technicians. The Air Force has several research efforts underway to examine, quantify and improve the experience of its maintenance technicians. What can be said with a measure of certainty is the Air Force acknowledges a decrease in experience in its maintenance technicians. It is therefore important that sensors, at least at the organizational level of maintenance, be as easy to maintain as possible encompassing ease of maintenance and self-diagnostic capabilities.

2.1.2 Operational Conditions Sensors Encounter

In addition to the environmental factors that must be considered when designing wireless sensing systems for use in Air Force aircraft, operational factors must also be considered. In order to be a viable alternative to wired sensors for the Air Force, wireless-sensing technology must be able to operate under the demanding conditions associated with high performance military aircraft. There are extreme temperature differentials within discrete aircraft systems. For example, aircraft avionics systems generate significant heat during operation and aircraft engines range in temperature from ambient air temperature at the intake to exhaust temperatures of several hundred degrees. All aircraft have many hydraulic systems, which operate at extremely high pressures, in excess of 3,000 psi. Any wireless sensing application for these systems must be able to withstand and perform given this extreme pressure and temperature range. Currently there are many commercial applications of wireless sensing technology that operate in high temperature and high-pressure environments. However, there are other stresses placed upon components that are completely unique to aerospace vehicles.

There are unique stresses placed upon sensing systems resulting from flight. Aircraft undergo significant barometric pressure changes from take off at sea level to cruising altitude that may exceed 40,000 feet. Fighter aircraft, in particular, face the added stress of encountering multiple G-forces during flight. This, coupled with the high frequency vibrations typical in supersonic flight, represents additional stressing factors military aircraft sensing systems must be able to handle. It is also typical that given certain operational missions, an aircraft will experience extremes in positive and negative G-forces, as well as vibrations, all within a matter of seconds.

2.1.3 Key Sensing System Characteristics

Applying the previous characterization of the Air Force maintenance and operational environment to wireless sensing technology defines the key characteristics for wireless sensing applications to Air Force aircraft systems. In order to best operate in the Air Force environment, wireless sensing systems should be resistant to extreme and rapid temperature changes, both external and internal to the system. The sensing system should also be able to function properly, despite stresses placed upon it by high Gs and

dramatic internal or external pressure variations. Additionally, no matter where the sensor is mounted in the aircraft, it should have some measure of protection against the elements: rain, wind, snow etc. These sensors should also be easily removed, replaced, maintained and repaired and require little or no special equipment or environmental controls.

2.2 Proposed Maintenance and Operational Characteristics of Wireless Sensing Systems

There are several factors to consider when developing a sensing system for use in military aircraft. First and foremost, the system must operate as it was designed in spite of the relatively harsh Air Force maintenance and operational environment. The previous section characterized the environment and the challenges the Air Force environment represents to system design. However, there is another factor of paramount importance when describing the desired characteristics of a wireless sensing system, component life span. Specifically, the greater the Mean Time Between Failure (MTBF) the better. An increased MTBF can mitigate other concerns such as difficulty of replacement or component cost. The more frequently a component or system fails the more inexpensive and easy to replace it must be to off set frequent failure. Conversely, it can be expected that a component with a very high MTBF might be more expensive but, due to the life span of the component, additional maintenance for this component is less of a concern.

The ability to calibrate, monitor, perform fault isolation, remove and replace a system or one of its components characterizes the system or component's ease of maintenance. The ability of technicians to perform maintenance on a specific system combined with how frequently that system fails, contributes to how long the aircraft is out of commission. As mentioned earlier, a high MTBF can somewhat mitigate a system or component that requires a significant amount of time to remove, repair and replace. However, there must be a balance between component life-span and ease of maintenance. Given the Air Force's current concern over maintenance technician experience, it would seem that ease of maintenance is of even greater concern. Additionally, in many instances, components, once fielded, fail to exhibit the MTBF rate originally expected and established during development.

Ideally wireless-sensing systems would possess certain ease of maintenance characteristics. They should have, to the greatest extent possible, self-monitoring, self-cleaning, self-calibrating and self-diagnostic capabilities. The more the system or component can do by itself the less reliance will be placed on maintenance technicians to properly perform these tasks. The system should be easily accessible and easy to remove. Another key ease of maintenance feature is the ease to which fault isolation can be performed. Quick and easy diagnosis and fault isolation enhance overall aircraft availability by dramatically reducing aircraft downtime due to system maintenance.

The other major concern in aircraft sensing system development, in addition to operational capability and ease of maintenance, is cost. Ideally, wireless sensors would

be low cost, or near the same cost as an older maintenance system or process they are replacing. As mentioned earlier, they should not require any additional, special tooling or environmental controls that drive up cost. Similarly, replenishment stocks should be easily transportable by both military and commercial means, i.e., "FedEXable." The Air Force has placed a premium on reducing the logistics footprint for deployed operations. Replacement parts and subassemblies that require little space and can be shipped commercially represent the direction in which the Air Force is heading with its Agile Combat Support initiatives and its support of the AEF.

2.3 Aging Fleet Considerations

The Air Force's fleet age is increasing, as the interval between new weapons system acquisitions is growing longer. The Air Force is devoting significant resources to combat this issue. With the projected increased cost of acquisition and operations of new systems the Air Force has extended the service life of many of its aircraft well beyond its design lifecycle. For example the B-52, a Vietnam era aircraft, is still in service and is a major part of the Air Force bomber fleet. The F-15 was first fielded in the Air Force inventory in the mid-1970s and is still the Air Force's premier Air Superiority Fighter. The F-16 has undergone multiple modifications and upgrades in its subsequent production runs, Blocks 30, 40 and 50, in order to meet Air Force mission needs. The examples are many; the point is that the Air Force will, for the foreseeable future, be devoting more and more resources to the modernization of its existing fleet. It is this area where the insertion of new technology will find its greatest inroads.

One effective means for facilitating integration of new technology into legacy systems is to minimize the intrusiveness of the new technology. Plainly stated, the degree to which wireless sensing technology can replace current sensing and monitoring systems with a minimum of overall system redesign will closely mirror the degree to which this technology will be adopted across the spectrum of Air Force weapons systems. A common phrase used in Air Force aircraft maintenance is, "Form, Fit, Function." Successful wireless sensing systems will have parity of form, fit and function with the systems they monitor or they should have superior form, fit or functional characteristics. However, care must be taken to ensure that the inclusion of wireless sensing technology does not interfere with existing aircraft systems. Similarly, with a general application of wireless sensor technology, more aircraft can take advantage of the power and cost payoff of this technology. This enables the Air Force to buy one system or component for use on many of its aircraft as well as increasing the market for wireless sensing system vendors, which should bring costs down.

There are additional benefits to the incorporation of wireless sensing technology into exiting Air Force aircraft. The use of a mature wireless sensing technology can imply the ability to remove or at least not use in place wiring systems. The removal of the unneeded wiring represents a significant weight saving and not using wire as a transmission media eliminates tedious and time-consuming maintenance tasks relating to fault isolation and repair of wiring malfunctions. The relatively small size of wireless sensing technology also has the appeal of being able to locate sensors in previously

inaccessible areas. This has significant implications for antenna placement, avionics system configuration and the monitoring of external fatigue indicators to name a few. Key to the success of wireless sensing technology in this application is the ability to tie this new sensing technology to existing data bus systems for the capture and reporting of data. There is the potential application of using wireless sensing technology in areas that are *leading indicators* but have not been monitored by sensors due to technological limitations. This opens up a whole new view into the aircraft's health.

To further facilitate the integration of wireless sensing technology into existing Air Force aircraft, the system's sensing improvements could be designed as discrete avionics, engine, environmental and airframe packages. These packages could then be scheduled for installation in conjunction with programmed depot maintenance requirements. This will minimize aircraft down time for installation since the aircraft will already be down for periodic maintenance providing easy access to all its major systems.

2.4 Best Application Considerations

The best application or point of insertion for wireless sensing technology is in areas where the most *"bang for the buck"* can be realized. Targeted systems should be high cost systems with high failure rates. Typically the monitoring systems characterized by high failure rates and high cost are avionics and engine monitoring systems. By employing the packaging methodology mentioned previously, the development of avionics and engine monitoring wireless sensing technologies could lay the groundwork for further advancement of wireless sensing technology in other systems.

The further development of wireless sensing technology could lead to the reduction of *hard* time inspections, inspections performed during programmed depot maintenance. With the ability to monitor an increased number of factors, it is conceivable to monitor most, if not all, key components within an aircraft system and have these sensors actively report system degradation. This could preclude the need for many periodic inspections, resulting in significant manpower savings as well as aircraft down time. With this improved sensing capability, sensing data could be used to perform prognostic analysis and facilitate proactive maintenance management. For example, improved sensing data could be coupled with existing avionics operational data and used in trend analysis. Trend analysis involves analyzing sensor measurements from differing locations within the avionics system in an attempt to detect and predict component failure before it occurs. Improvements in automated data analysis tools will further enhance the prognostic capability represented by the improvements in wireless sensing technology.

3. Technology and Product Identification

3.1 Overview

In this section we will develop the methodology for quantitatively ranking a number of identified products or technologies. In this case, the team applied this methodology to the selection of suitable wireless sensor products and technologies, but the methodology itself is quite general. It is based on the Quality Function Deployment (QFD) methodology.

Using this selection methodology, the team determined a few products and technologies that appear to be most promising in the area of aircraft maintenance. These selected products and technologies will be discussed in further detail in Section 4.

3.2 Methodology

While it is relatively straightforward to identify what technologies and products are available in the marketplace, it is another matter to determine which are best suited for any given application. The situation is further complicated by the multi-dimensional space of selection criteria.

How, for example, does one choose the relative value of a wireless sensor system that has two channels at 8,000 samples per second each versus a system that has four channels at 5,000 samples per second each? One way would be to look at the total data throughput, e.g., 16,000 samples per second for the first system versus 20,000 samples per second for the second. On this basis the second system would appear to be better. However, it may be that for a given application, the data rate of 5,000 samples per second is not sufficient. The selection process is further complicated when one considers the full range of characteristics that make up a system, e.g., range, power, number of channels, size, weight, transmission frequency, transmission type (FM, AM, spread spectrum, etc.), and may others.

3.2.1 Selection Criteria

In order to help in selecting a few good candidates from a large range of possible systems, a quantitative methodology is helpful. Let us first explore the criteria used for making selection judgments, and then we will define the algorithm by which the judgments will be made. For the selection of wireless sensor systems, ADL and the Air Force Research Laboratory collaborated to define a set of objective criteria that provided a basis for scoring each system. Two classes of criteria were defined: General or System Criteria and Performance Criteria. Table 3-1 lists the criteria in each class for the commercial products being evaluated. For the patented technology, only two criteria were used due to the unknown nature of their state of development. The technology criteria are shown in Table 3-2. Note the definitions for the Technology Criteria shown in Table 3-2 are the same as the corresponding System Criteria shown in Table 3-1.

Each system under consideration was rated using the indicated criteria with a score from 1-10. This rating was assigned by ADL. Each criterion, in turn, was weighted in terms of its relative importance. This weight, called Criterion Importance (CI), was assigned by AFRL with the value noted for each System, Performance, or Technology criterion in Table 3-1 and Table 3-2. The weight given to Criterion Importance was selected according to the following scale:

CI	Characteristic
1	Not important
2-4	Interesting but not essential
5	Important
6-9	Essential
10	Most important, show-stopper

Table 3-1: Criteria Used in Product Ranking Methodology

System Criteria	CI
Deployability (e.g., footprint, volume, mass)	8
Supportability (e.g., reliability, maintainability)	10
Cost	5
Readiness (NASA's Readiness levels)	5
Applicability	7
Level of Integration (e.g., network vs. sensor)	6

Performance Criteria	CI
Communication Range	10
EM Compatibility	10
Bandwidth	7
Sensitivity	7
Power Consumption	10
Environmental	10

Table 3-2: Criteria Used in Technology Ranking Methodology

Technology Criteria	CI
Applicability	7
Integration	6

Each System, Performance, or Technology Criterion, as mentioned, was scored in the range of 1-10. The value assigned is identified as the Criteria Ranking (CR). The translation from subjective to objective measure for each was guided by the following considerations.

System Criteria for products

- *Deployability*: Rated with respect to how easily this technology can be put into aircraft with minimal invasiveness. Consideration of system mass represented 80% of the total rating, while other factors such as mounting ease, footprint, and volume constituted the remaining 20% of the rating score.
  Very invasive was give a rating of 1, and
  Non-invasive was given a rating of 10.

- *Supportability*: Evaluated based on "How difficult are these new systems going to be to support, repair, maintain, etc.?" Factors such as reliability due to battery life, redundancy, and self-test were considered. In addition maintainability was considered in terms of the ease of servicing, e.g., changing batteries.
  Frequent support needed rated a 1, and
  Infrequent support rated a 10.

- *Cost*: No specific cost guidelines were established, but each of the solutions was rated with respect to the other systems under consideration. Two cost factors were included: component cost and cost of implementation.
  High cost rated a 1, and
  Low cost rated at 10.

- *Readiness*: While most of these criteria are self-explanatory, the NASA Readiness levels may need some explanation. This criterion uses a codified approach adapted from NASA's 1991 Integrated Technology Plan to rank the maturity of a technology. Table 3.3 defines the NASA readiness levels.

Table 3-3: System Readiness Level defined by NASA

Basic technology research	
Level 1:	Basic principles observed and reported
Research to prove feasibility	
Level 2:	Technology concepts and/or application formulated
Level 3:	Analytical and experimental critical function and/or characteristic proof of concept
Technology Development	
Level 4:	Component and/or breadboard validation in laboratory environment
Technology Demonstrations	
Level 5:	Component and/or breadboard validation in relevant environment
Level 6:	System/subsystem model or prototype demonstrated in relevant environment
System/Subsystem Development	
Level 7:	System prototype demonstration in an aviation environment
System Test, Launch, and Operations	
Level 8:	Actual system completed and "flight qualified" through test and demonstration
Level 9:	Actual system "flight proven" through successful mission operations

- *Applicability*: Each system was rated as to its applicability to the stated goals of this research effort, "…investigate and demonstrate technology to collect system/component performance data required to predict component failures for legacy aircraft."
  No applicability rated a 1, and
  Specific design for aircraft failure prediction rated a 10.

- *Level of Integration*: Rating based on extent to which system included a multi-point sensor suite, network solutions, specific sensor solutions, single point solutions, and wireless network solutions with applicability to sensors.
  Single component rated a 1, and
  Full network system solution rated a 10.

Performance Criteria for products

- *Range*: Communication range is rated for each system with consideration given to mode of transmission (e.g., acoustic, optical, RF) and operating environment, especially in consideration of the RF rich environment of a typical military aircraft.
  Short range (a few meters) rated a 1, and
  Long range (many kilometers) rated a 10.

- *Electromagnetic compatibility*: EMC of any technology solution is critical with consideration including generation of EMI, susceptibility to normal aircraft EMI, and susceptibility to electronic countermeasures.
  Incompatible rated a 1, and
  Fully compatible and robust systems rated a 10.

- *Bandwidth*: Bandwidth is rated on the amount of information transferred per unit time. Of special note are sensors with local processing to reduce bandwidth requirements, a trade-off between bandwidth and range, and spread spectrum systems that permit improved data integrity and security.
  Small bandwidth systems less than 19.2k bits/s rated a 1, and
  Wide bandwidth systems greater then 1M bits/s rated a 10.

- *Sensitivity*: Sensitivity is a fusion of several physical application specific parameters, including signal-to-noise ratio (SNR), accuracy and repeatability, and precision and resolution.
  Low sensitivity, low SNR, inaccurate, and imprecise systems rated a 1, and
  High sensitivity, high SNR, highly accurate, and very precise systems rated a 10.

- *Power*: Power consumption must be low to maintain minimal invasiveness and supportability of the technology. Of note are RF solutions that energize sensors via the same wireless link as is used for communication. Alternatives include pulling power from batteries, the aircraft power bus, or power harvesting from structural or aerodynamics.
  High power consumption greater than 1 W rated a 1, and
  Low power consumption less than 10 mW rated a 10.

- *Environmental*: Tolerance to extreme environmental conditions is essential. Primary factors of interest are temperature, dynamic loading, vibration, and humidity.
  Non-function in operating environment rated a 1, and
  Fully functional rated a 10.

Technology Criteria for technology
(same as corresponding criteria used for products)

- *Applicability*: Each system was rated as to its applicability to the stated goals of this research effort, "...investigate and demonstrate technology to collect system/component performance data required to predict component failures for legacy aircraft."
  No applicability rated a 1, and
  Specific design for aircraft failure prediction rated a 10.

- *Level of Integration*: Rating based on extent to which system included a multi-point sensor suite, network solutions, specific sensor solutions, single point solutions, and wireless network solutions with applicability to sensors.
  Single component rated a 1, and
  Full network system solution rated a 10.

3.2.2 Ranking Computation

The ranking method used is based on Quality Function Deployment (QFD), which is a method for structuring product planning and development. It enables a development team to specify clearly the user's wants and needs and to evaluate systematically the impact proposed products have on these needs. The methodology developed originally in the 1960's in Japan and was introduced in the US in the 1980's. A full QFD analysis can be quite complex, but we have extracted the general strategy offered by QFD and used a greatly simplified version for this analysis. Nevertheless, the fundamental benefits of QFD are retained here. Specifically we have

- Identified stakeholder needs

- Ranked concepts

- Benchmarked existing products
- Established preliminary specifications
- Linked these specifications to user requirements
- Built team consensus

To implement our version of QFD, we have selected two measures for each criterion, i.e., Criterion Ranking (CR) and Criterion Importance (CI). These are combined to give an overall score for each system. Initially a separate score was given to each system for the System Criteria and for the Performance Criteria. Individually these scores were used to help winnow out the best systems for demonstrations and gathering further information. Some of the System Criteria are highly dependent on the state of commercial maturity. Early devices may, for example, have a large footprint or may be heavy simply because it was easy to get a prototype built using available materials. As the product matures, it is expected that many of the physical attributes will become increasingly attractive including size, weight, and cost.

Nevertheless, for each of the systems, a score was computed as the weighted average of each Criterion Ranking over the range of criteria. Mathematically, the score may be computed as:

$$Score(\%) = \frac{\sum CR * CI}{10 * \sum CI} * 100 . \qquad (3\text{-}1)$$

This equation was used to compute the scores in all of the tables in the sections on ranking results, Sections 3.3 and 3.4. Because some of the information on some of the sensor systems was incomplete, the value of each ranking was quantified as a percentage of the total input data that was available.

3.3 Product Evaluation

We shall first apply the ranking methodology to the systems that are commercially available. The process will be used to determine which of the systems or products deserve further study. In a later section, we will describe a similar evaluation for the patented technology that has been identified.

3.3.1 Identified Products and Systems

ADL uncovered a large number of products and systems in an initial search of the literature, Internet, patents, and conference publications. After a rough screening to eliminate any obvious mismatches, a total of eleven candidate products or systems were selected for further evaluation. These are itemized as follows.

- **WINS (Wireless Integrated Network Sensors) by Sensoria**: These devices are customizable, sensor-ladened networked nodes with mobile user interfaces. The system was developed in conjunction with UCLA and Rockwell Sciences. It permits a range of sensors to be coupled to the node, including seismic, acoustic, acceleration, IR, digital camera, etc. The wireless link is implemented on a 900 MHz or a 2.4 GHz spread-spectrum channel with a typical range to 100 m. Field trials, however, demonstrated range out to 1.6 km. Further information is available at www.sensoria.com.

- **Advanced Telemetrics International**: ATI makes sensors with integrated telemetry for point-to-point connectivity between sensors and data acquisition systems. They specialize in non-contact, especially where data must be transmitted from a rotating system to a stationary receiver. Point-to-point systems transmit data at ranges up to two miles. The transmitters themselves are miniaturized and are available for most types of sensor transducers. Signals to be transmitted may include torque, strain, acceleration, torsional vibration, thrust, and bending. Further information is available at www.advancedtelemetrics.com.

- **Micro-wireless Instrumentation System (μWIS) by NASA**: This sensor system is a small battery operated device that measured temperature in the crew module on the Space Shuttle during mission STS-101. The wireless link operates at 916 MHz with 1 mW output power. The system has three units, a Transmitter/Sensor Unit, a Receiver Unit, and a Recorder Unit. It was developed to support the μWIS flight experiment being conducted in partnership between Kennedy Space Center, Johnson Space Center and Invocon, Inc. The experiment is part of the Integrated Health Management initiative for testing the feasibility of wireless sensors for space applications.

- **SmartSensors by Computational Systems, Inc.**: CSI manufacturers wireless RF SmartSensors for on-line condition-based monitoring. Each system consists of an RF transceiver and up to 64 SmartSensors located within a 300 ft. radius. The SmartSensor analyzes vibration and temperature data, providing machinery condition assessment. SmartSensors are battery powered and optionally have battery powered RF transceivers. The Model 4100 was identified by CSI as the best candidate for the maintenance application. It currently measures and transmits temperature and vibration data, but could be modified to handle many other types of sensors. Further information is available at www.compsys.com.

- **RF Data Corp.**: RF Data manufactures a line of spread spectrum transceivers with integrated analog I/O interfaces and built-in point to multi-point protocols. The wireless connections operate in the 902-928 MHz ISM band with a frequency-hopping scheme. The device supports four input channels at 12 bits resolution with an option to go to 16 bits. Input can be

either a voltage source or current source selectable for a variety of different ranges. Further information is available at www.rfdatacorp.com.

- **CrossNet by Crossbow Technologies, Inc.**: The CrossNet architecture provides for real-time remote sensing and data acquisition using the Bluetooth wireless protocol. Each CrossNet note can control and monitor up to four sensors and communicate via Bluetooth to a CrossNet hub up to 10 m away. The hub can be any Bluetooth enabled device including a PC, PDA, web server, etc. Further information is available at www.xbow.com.

- **ICHM (Intelligent Component Health Monitor System) by Oceana Sensor Technologies**: These devices are part of a smart, wireless, network-capable sensing system. ICHM provides for machinery health monitoring and industrial process control. It incorporates multiple sensing devices to measure vibration, temperature, acoustics, and pressure among other parameters. At the time the Oceana system was originally identified, the ICHM had no wireless interconnect. In September of 2000, Oceana announced the release of a Bluetooth enabled ICHM product platform. Further information is available at www.oceanasensor.com.

- **NoWire™ by HiTech Equipment Corp.**: HiTech has developed a series of wireless data devices for data acquisition. Separation between the transmit and receive unit may be up to 100 ft. with greater distances possible by using repeaters. The NoWire™ Data Collection Unit (DCU) processes, displays, and stores data and can be interfaced to an external PC. Further information is available at www.hte.com.

- **Wireless networked sensors by Wilcoxon Research, Inc.**: Wilcoxon has formed a new division, Wilcoxon Labs, to focus on researching and developing innovation technologies, including wireless networked sensors. An experimental RF network has been developed that operates in the UHF band at 315 MHz with a data rate of 2400 baud. Sensors contain a microcontroller, real time clock, and data memory. Work is being done in conjunction with NIST ATP. Further information is available at www.wilcoxonlabs.com.

- **EZCom by Grayhill, Inc.**: EZCom is a wireless network designed for industrial and manufacturing environments. It operates in the 900 MHz band in a point-to-point or a multi-point data communications mode and may be used in conjunction with sensors and control hardware. Range is up to about 15 miles in unobstructed paths. Using Direct Sequence Spread Spectrum, the device has low susceptibility to interference. Further information is available at www.grayhill.com.

- **Wireless Site Extender (WISE) by Synetcom Digital, Inc.**: WISE is part of a family of wireless telemetry systems. It can accommodate up to 32 analog/digital sensors with transmission ranges up to several miles using a spread spectrum signal. The WISE host directly interfaces to an RTU-1 datalogger, which can report daily sensor reading to a host PC and can page or e-mail when an alarm condition is detected. Further information is available at www.synetcom.com.

3.3.2 Product Ranking Results

The ranking methodology described 3.2.2 was applied to help determine which of the systems identified in the previous section were most suitable for the aircraft maintenance application. Rank ordering for System Criterion and Performance Criterions were done separately.

3.3.2.1 System Criterion

Table 3-4 shows the scores that were given to the different systems for each of the Systems Criterion. The weights or Criterion Importance are also shown. At the bottom of each column is the score for the corresponding system expressed as a percentage.

Table 3-4: Tabulation of Scores and Resulting Rankings for the System Criteria Itemized in Table 3-1.

	W	WINS	ATI	uWIS	CSI	RF Data	CrossNet	Oceana	HiTech	Wicoxon	Grayhill	Synetcom
Deployability	8	8	7	8	6	6	5	5	5	5	5	3
Supportability	10	8	8	5	7	5	6	6	6	5	5	4
Cost	5	5	7	7	5	6	3	3	3	5	4	3
Readiness	5	6	7	7	6	7	6	5	5	4	6	5
Applicability	7	9	8	8	6	6	7	7	7	7	4	6
Integration	6	9	3	3	6	6	7	3	3	7	5	7
		77%	68%	63%	61%	59%	58%	50%	50%	55%	48%	46%

Based purely on the System Criteria, which relates in some measure to the degree of maturity of the product development, we see that the WINS system by Sensoria has the high score. ATI, μWIS, CSI, RF Data and CrossNet received mid-level scores. Before we analyze the results, let us see how the same systems scored in terms of the Performance Criteria.

3.3.2.2 Performance Criterion

Table 3-5 shows the scores that were given to the different systems for each of the Performance Criterion. The weights or Criterion Importance are also shown. At the bottom of each column is score for the corresponding system expressed as a percentage. In addition, the scores for the System (General) Criterion are also shown along with an overall ranking that is computed as the product of the System and Performance Criteria for each system.

Table 3-5: Tabulation of Scores and Resulting Rankings for the System Criteria Itemized in Table 3-1.

	W	ATI	WINS	CrossNet	CSI	uWIS	RF Data	Grayhill	Oceana	HiTech	Synetcom	Wicoxon
Range	10	9	8	5	8	4	9	9		7	9	5
EMC	10	5	6	6	6	8	5	5	6	6	5	5
BW	7		4	7		3	4	8	3	3	7	4
Sensitivity	7			8	6		4		6	6		4
Power	10	5	3	7	3	6	6	3		3	3	4
Env.	10	7	7	6	7	7	7	6	7	7	5	4
Perf. Score		65%	57%	64%	60%	58%	60%	61%	57%	54%	57%	44%
Gen. Score		68%	77%	58%	61%	63%	59%	48%	50%	50%	46%	55%
Total Score		44%	44%	37%	37%	36%	36%	29%	28%	27%	26%	24%

For the Performance Criteria, ATI and Crossbow receiving the highest scores while all the other systems except Wilcoxon bunched together at a mid-range level.

Taking the product of the System (or General) Score and the Performance Score, we arrive at the total score, which is shown in the last line in Table 3-5. The high-ranking systems in this case are those that have both good performance rankings and good system rankings. The top four systems ATI, WINS, CrossNet, and CSI were chosen for further consideration.

3.3.3 Selected Commercial Products

Each of the four systems with the highest overall ranking were targeted for more in-depth investigation. Of the four, all but CSI were demonstrated during the fourth quarter of 2000 and the first quarter of 2001. The ATI system was demonstrated for AFRL and TASC at ATI in Dayton, OH during January 2001. Crossbow demonstrated their system at ADL's Cambridge, MA facility on October 16, 2000 for ADL personnel and again as part of the Intelemetric workshop on January 30, 2001 for both ADL and TASC personnel. The WINS system by Sensoria was demonstrated at Sensoria in Santa Monica, CA for AFRL, TASC, and ADL personnel on October 25, 2000. No demonstration for the CSI system could be arranged. The company was contacted to see if they had systems that could be observed in the Dayton or Boston area, but we were unable to schedule a demonstration.

More information about these systems and the results of the demonstrations is presented in the following section.

3.4 Technology Evaluation

Let us now apply the ranking methodology to the patented technology that has been discovered in the area of wireless sensor systems.

3.4.1 Identified Technology

ADL uncovered a large number of patents through an initial search of the literature, Internet, patents, and conference publications. After a rough screening to eliminate any

obvious mismatches, a total of ten candidate patents were selected for further evaluation. These patents relate to wireless sensing and information distribution. They are itemized as follows in order of the rankings as discussed in the next section.

- **US #6,009,356 "Wireless transducer data capture and retrieval system for aircraft"**: Patent issued to Raytheon on December 28, 1999. The patent addresses a safety and surveillance recorder system for aircraft that incorporates wireless sensors to monitor critical components and operational characteristics of an aircraft. The technology revolves around the strategic placement of wireless sensors to monitor engine temperature, oil pressure, hydraulic pressure, and strain gauges. Wireless transmission to one or more black-box recorders aid in the reconstruction of catastrophic events and performance history. In this invention, each sensor is presumed to have an independent power supply. On-line access to the patent is available at www.delphion.com/details?&pn=US06009356__.

- **US #5,809,220 "Fault tolerant distributed control system"**: Patent issued to Raytheon on September 15, 1998. The patent covers a fault tolerant distributed intelligent control system for sensing and actuation via a fiber optic communication media interconnecting two or more intelligent nodes. Each node is a digital control and communications processor and operates autonomously. The interconnecting fiber optic media are bi-directional serial busses. The combination of processors and media provide a low cost, highly reliable distributed control system that is particularly applicable to aircraft and other vehicles. On-line access to the patent is available at www.delphion.com/details?&pn=US05809220__.

- **US #5,982,297 "Ultrasonic data communications system"**: Patent issued to The Aerospace Corporation on November 9, 1999. It describes an ultrasonic data communications system that allows bi-directional transfer of data through a coupling medium without the use of electrical power wires for controlling embedded sensors and actuators. Such a system permits embedded wireless sensors in motor casings or propellant tanks without the use of connected wires. It provides for power and data communication to sensors enclosed in conducting materials where penetration by RF waves is impossible or impractical. On-line access to the patent is available at www.delphion.com/details?&pn=US05982297__.

- **US #5,798,458 "Acoustic catastrophic event detection and data capture and retrieval system for aircraft"**: Patent issued to Raytheon on August 25, 1998. It addresses an acoustic sensor system for detecting failures in aircraft in the event of a catastrophic event. The acoustic sensors are distributed strategically about an airframe and communicate to monitor systems via wire or wireless units. Catastrophic acoustic events, such as an explosion,

gunshot, or structural failure are recorded for later analysis. On-line access to the patent is available at www.delphion.com/details?&pn=US05798458__.

- **US #5,907,491 "Wireless machine monitoring and communication system"**: Patent issued to CSI Technology on May 25, 1999. The patent covers a machine monitoring and communication system with devices that sense physical characteristics, such as vibration or temperature, and deliver these readings via a wireless transmission. A command station executes machine status polling using a time-division communications protocol. To conserve power, machine monitors are turned on only at preprogrammed times. Repeaters are employed to assist in propagating wireless transmissions throughout the system. On-line access to the patent is available at www.delphion.com/details?&pn=US05907491__.

- **US #5,825,286 "Vehicular data collection and transmission system and method"**: Patent issued to SemiSystems, Inc., on October 20, 1998. The patented invention covers wireless sensing of vehicle operational parameters such as tire pressure, wheel temperature, and vibration. The sensors are mounted on wheel modules with RF transmission of sensor data to another location on the vehicle. On-line access to the patent is available at www.delphion.com/details?&pn=US05825286__.

- **US #5,995,000 "Wireless compass for vehicles"**: Patent issued to Lear Corporation on November 30, 1999. The patent addresses a wireless compass sensor for vehicles and includes a wireless heading sensor with a transmitter and a compass display with a complementary receiver. The display is installed in a location most convenient for the vehicle operator, ease of installation, and reliability. The sensor is installed in a location with minimal magnetic interference from the vehicle. On-line access to the patent is available at www.delphion.com/details?&pn=US05995000__.

- **US #5,942,991 "Resonant sensor system and method"**: Patent issued to Diversified Technologies on August 24, 1999. The patent provides for a system to remotely measure environmental conditions using a resonance sensor that varies in correspondence with changes in the environmental condition at the sensor. The sensor emits an electromagnetic return signal representing the state of resonance characteristic when an excitation signal impinges on the sensor. A generator located away from the sensor generates the excitation signal. The sensor remotely detects and measures the environmental condition. On-line access to the patent is available at www.delphion.com/details?&pn=US05942991__.

- **US #5,481,481 "Automated diagnostic system having temporally coordinated wireless sensors"**: Patent issued to Architectural Energy Corporation on January 2, 1996. The patent covers a diagnostic system that

makes use of knowledge-based controllers and multiple wireless data loggers. The system collects temporally coordinated data indicative of real time operation of a system under test. The diagnostic system controller automatically architects a plan to collect data and calculates performance factors from the collected data. Through a comparison of calculated performance factors with optimum and typical failure modes, the system identifies performance problems in the system under test. On-line access to the patent is available at www.delphion.com/details?&pn=US05481481__.

- **South Africa #946,337 "Wireless sensor system to test the operation of shock absorbers of a vehicle's suspension"**: Patent issued to Dirk Kleynhans, Cape Town, South Africa. Patent teaches the incorporation of a method of determining displacement of a sprung part of a vehicle with respect to the unsprung part (ground) by means of ultrasonic ranging. Data is transmitted by means of a remote wireless communications link, possibly an ultrasonic data link.

3.4.2 Technology Ranking Results

The ranking methodology described earlier was applied to determine which of the patented technologies in the previous section are most suitable for the aircraft maintenance application.

Table 3-6 shows the scores that were given to the different patents in terms of the technology Applicability and Level of Integration. The weights or Criterion Importance are also shown. At the bottom of each column is score for the corresponding technology expressed as a percentage.

Table 3-6: Tabulation of Scores and Resulting Rankings for the Technology Criteria Itemized in Table 3-2.

	W	6,009,356	5,809,220	5,982,297	5,798,458	5,907,491	5,825,286	5,995,000	5,942,991	5,481,481	946337
Applicability	7	9	8	9	7	5	6	5	6	3	4
Integration	6	8	7	4	6	6	4	4	2	5	3
		85%	75%	67%	65%	55%	51%	45%	42%	39%	35%

Three of the top four patents were issued to Raytheon. Specifically,

- US #6,009,356 "Wireless transducer data capture and retrieval system for aircraft"
- US #5,809,220 "Fault tolerant distributed control system"
- US #5,798,458 "Acoustic catastrophic event detection and data capture and retrieval system for aircraft"

The fourth high ranking patent was from Aerospace Corporation:

- US #5,982,297 "Ultrasonic data communications system"

Each of these four high scoring patents was targeted for more in-depth investigation as described later in Section 5.

3.5 μPower Technology Identification

During the course of the study for AFRL, it became clear that an auxiliary aspect of wireless systems needed to be covered. In particular, we needed to evaluate how the remote, wireless sensor nodes were to be powered. The virtue of wireless communication, especially in legacy aircraft, is that new wiring does not need to be installed. In many situations, while data communication would require additional wiring, an airframe electrical power bus would be available at the sensor site. In these situations, the wireless technology has clear implementation benefits.

Alternatively, if a power bus is not available, then other sources must be considered. Candidates included one of a number of power storage devices including batteries and fuel cells. Opportunistic power harvesting is another option, especially considering the high-energy environment in which aircraft operate.

To this end, a wide variety of, so called, μpower sources were identified and evaluated qualitatively. A formal QFD analysis was not conducted, but the findings offered herein

should provide enough information so that any follow-on studies can be adequately framed.

The field of μpower devices was divided into four major categories, and specific examples for each of these categories were identified. Table 3-7 lists the systems. An asterisk in the table indicated a μpower source that is perceived to be the best match for near-term wireless sensor applications.

Table 3-7: μPower Energy Devices for Wireless Sensor Devices

Microbatteries	
	Oak Ridge National Laboratory
	Brigham Young University, Bipolar Technologies, Inc.
	Korea Institute of Science and Technology
	Nuclear Microbatteries, University of Wisconsin, Madison, DOE
Micro-fuel cells*	
	Case Western Reserve University
	Manhattan Scientifics, Inc.; Hockaday Fuel Cell
Micro-generators	
	Miniature High Voltage Solar Cell Array, Georgia Tech, NSF
	MIT Media Lab Parasitic Power Harvesting*
Micro-turbines	
	Micro Gas Turbine Engines, MIT
* *Best match for wireless sensor application*	

Only those device developments that were evaluated to be suitable for wireless sensor applications will be reviewed here.

3.5.1 Micro-fuel Cell at CWRU

This work has been on going under the direction of Prof. Robert F. Savinell. Their technology is oriented toward the development of a miniature fuel cell with a volume of 5 mm^3 that can be built using micro-fabrication techniques.[2] Multiple layers of fuel cell components are printed onto a substrate in a batch process. This enables high-volume, low-cost production. The prototype device uses hydrogen stored in a low-pressure hydride as the fuel source. Future versions are expected to operate on methanol. The research goal is to produce a device with 250 mW-hr of energy at a power level of 10-20 mW on a 2x2 cm^2 substrate area. Details are available at http://cheme.cwru.edu/People/Faculty/savinell/fcprog.html.

3.5.2 Micro-fuel Cell at Manhattan Scientifics, Inc.

The Manhattan Scientifics work in fuel cells grew out of research done at Los Alamos National Laboratory. The technology is under the direction of Richard Hockaday. He

[2] 5 mm^3 is about the size of a pencil eraser.

has named the device the Hockaday MicroFuel Cell™. An exploded view of the fuel cell is shown in Figure 3-1. It operates on a mixture of methanol and water to produce electricity. In late October 2000, this technology was integrated into a system called a Power Holster™, which was used to power a Nokia 6190 cellular phone for one month. Only one ounce of fuel was needed for this period of time. The fuel cell was able to deliver more than twice the battery energy of a 900mAh lithium battery. The Power Holster uses an array of the Hockaday MicroFuel Cells to continuously charge the phone when inserted in the holster. Details are available on-line at www.mhtx.com.

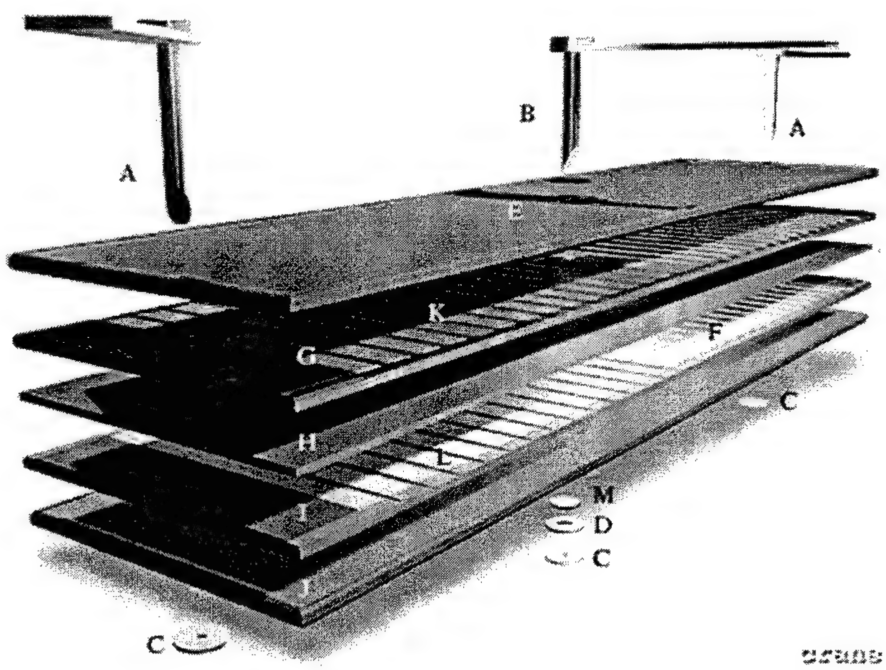

Figure 3-1: Exploded view of Hockaday MicroFuel Cell™. Components include (A) Air Electrode Contact Rivet, (B) Fuel Needle, (C) Rivet Fold Out, (D) Upper Gasket Ring, (E) Lower Gasket Ring, (F) Through Contacts, (G) First Set of Fuel Cells, (H) Fuel Manifold, (I) Second Set of Fuel Cells, (J) Air Manifold, (K) Air Electrodes, (L) Fuel Electrodes, and (M) Contact Washer. Source: http://www.mhtx.com/.

3.5.3 MIT Media Lab Parasitic Power Harvesting

The Media Lab at MIT has, for many years, been working on a variety of enabling technologies with demonstrations of the technologies embodied in more-or-less practical devices. Just as with wireless sensor nodes, providing for power in many of the Media Lab devices has been a chronic problem. As a result, the Lab has been working on a variety of power harvesting or power scavenging devices.

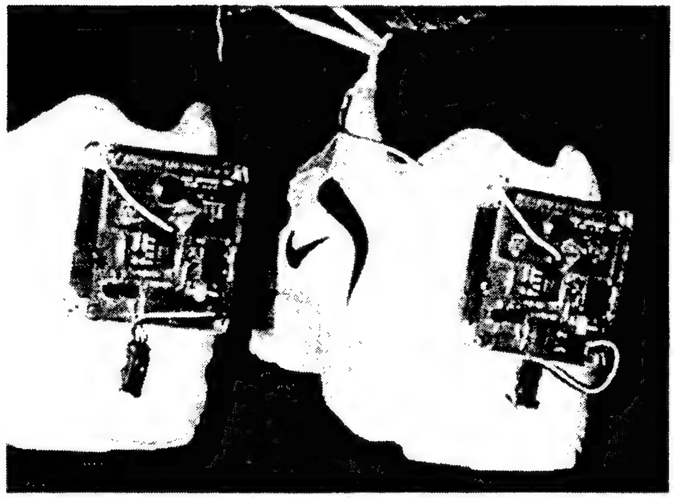

Figure 3-2: MIT power harvesting technology using piezo-materials of two types: a piezoceramic composite unimorph strip and a stave made from a multi-layer PVDF laminate. System built around piezoelectric shoes periodically broadcasts a 12-bit digital RFID as the bearer walks. Image Source: http://www.media.mit.edu/resenv/power.html.

A few of the better know successes are related to wearable systems, notably shoes where excess energy is available and readily harvested. Generation devices built into shoes are able to harvest the energy parasitically and convert it to electricity for other on-board power needs. Piezoceramic composites and PVDF (Polyvinylidene Fluoride) film laminates have both been tested. These systems have been used to power an RFID (radio-frequency identification) tag that periodically broadcasts a 12-bit digital message as the shoe moves about with the walker. Prototypes of these shoes are shown in Figure 3-2. A rotary magnetic generator was another demonstrated device. It was able to generate 250 mW of continuous power, but the device was obtrusive and not deemed to be practical for shoe systems. Nevertheless, it is clear that appropriately designed power harvesting systems can be designed to take advantage of available mechanical energy and convert it to electrical energy for use to power electronic systems. Further details are available at www.media.mit.edu/resenv/power.html.

4. Product Demonstrations

4.1 Demonstration Overview

In the last section we used the Quality Function Deployment (QFD) methodology to down-select those wireless sensor products that were most applicable to the aircraft maintenance application task. The four products with top scores in the QFD analysis were the WINS system from Sensoria, the ATI rotating wireless sensor system, the CrossNet system from Crossbow, and the SmartSensor system from CSI. All of the companies were contacted to arrange demonstrations, and these were set up for all but the CSI system. It was hoped that CSI would provide information about where to see their system in use at locations around the Boston and Dayton area. Unfortunately, it was not possible to arrange a demonstration.

In addition to the wireless sensor systems from Sensoria, ATI, and Crossbow, ADL developed a demonstration of our Intelemetric™ Systems architecture, which is a system to access and control sensor data via the Internet (or any other Ethernet network). The Intelemetric demonstrator was featured at a workshop in January 2001 in which representatives from many industries and TASC/AFRL worked to further define the requirements for such a systems.

This section covers the demonstrations held at ADL for the Crossbow and the Intelemetric systems, at Sensoria for the WINS system, and at ATI for their rotating wireless sensor systems.

4.2 ATI

Advanced Telemetrics International (ATI) is the manufacturer of remote sensors with integrated telemetry for point-to-point connectivity between sensors and data acquisition systems. The company has been in business since 1987.

A demonstration of ATI technology was presented to AFRL and TASC representatives in January 2001. ATI systems can connect to many types of sensors but strain gauges and temperature sensors are the most common applications so far. They have done extensive work with the automobile industry for measuring shaft torque loads and other applications that involve spinning shafts. ATI specializes in non-contact data coupling, e.g., for data collected on rotating systems and moving machinery.

The units that were shown to the team weighed a couple of ounces with typical dimensions of 1”x1”x2”. An example of one system is shown in Figure 4-1.

Range of the telemetry is limited by antenna length and physical environment surrounding the unit. Typical ranges for available systems is as follows:

- 2050 Series systems operate at 900 MHz out to a range of 500 feet
- 2060 Series systems transmit point-to-point at ranges up to 2 miles

Figure 4-1: Rotating wireless sensor package and receiver from ATI. System used extensively in monitoring of strain, torque, temperature and other signals on rotating shafts. (photo: www.advancedtelemetrics.com)

Power for the wireless transmitter is typically 9 volts DC but this can be scaled down to 5.5 volts in the current design. Even lower voltage could be incorporated in a custom design. A standard 9-volt battery will give 35 hours of operation for a 350-ohm strain gauge in a typical application. The telemetry unit has an automatic sleep mode that conserves battery power till activation.

4.3 Sensoria

Sensoria is a startup company that formed out of Rockwell and UCLA. They have focused on the wireless interconnect of conventional sensors. They have strong connections and funding commitments from the Department of Defense, principally the Defense Advanced Research Projects Agency (DARPA).

The Wireless Integrated Network Sensors (WINS) system was demonstrated at Sensoria on October 25, 2000 to representatives of AFRL and ADL. A discussion of the overall WINS family of products was presented along with a demonstration of their capability. Four wireless platforms comprise the WINS product line:

- WINS NG: enables fundamental wireless interconnectivity
- PicoWINS: supports multi-hop message and limited local processing
- WINS Imager: integrates camera and remote trigger for event capture
- WINS Vehicle Gateway: monitors vehicular systems for use at service centers

4.3.1 WINS NG

These systems are small, "lunch-box" sized, packages that contain the sensor interface, a processor, and telemetry radio. Presently the NG units are packaged for portability, but the functionality could be deployed in a targeted application for installation on aircraft

or ground support equipment. The WINS NG system was operated in August 2000 for 2 weeks at 29 Palms, CA with 37 nodes. The exercise involved the analysis and transmission of data from seismic, acoustics, and IR sensors. Data were transmitted at 256 samples/second on an RF carrier at 900 MHz.

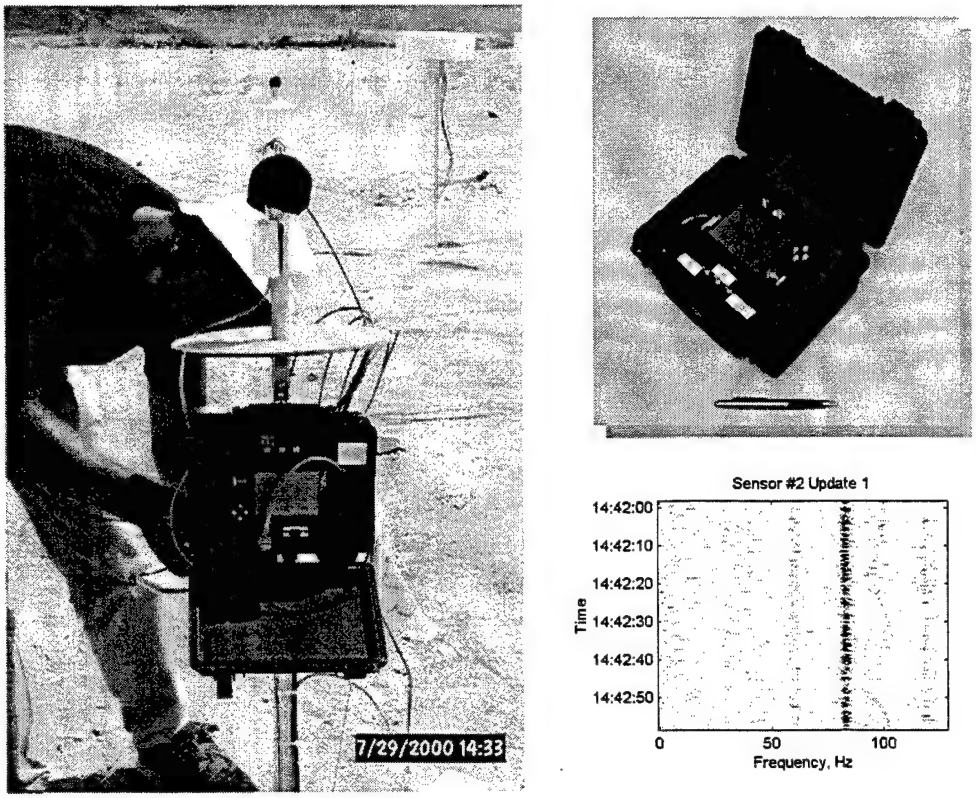

Figure 4-2: WINS NG 1.0. The photograph on the right shows the WINS NG 1.0 while the image on the left shows the unit as part of the 37-node system deployed at 29 Palms, CA. Three sensors collected seismic, acoustic, and IR data. The plot on the lower right shows the acoustic sensor output as a function of time and frequency. (images: Sensoria, Inc.)

Figure 4-2 shows one of the 37 WINS NG nodes that were used in the 29 Palms, CA field experiment along with a sample of representative data. Each node includes several components including:

- Global Position System (GPS) receiver,
- RF modem for two-way communication off-board
- Processor and platform control system
- Power management system
- PDA user interface

In addition, development Application Programming Interfaces (APIs) are available for building the WINS NG unit into an integrated system with multiple nodes. The architecture for the WINS NG system includes both sensor input and actuator output.

The processor architecture is divided into a continuous real-time subsystem that runs at extremely low power levels and a post-processing subsystems that runs at higher power levels but on a low duty cycle. The post processor can be invoked as needed to handle user specified processing tasks (e.g., check for certain events every 5 minutes or execute post processing only on external event trigger).

The WINS NG RF modem operates in the 2.4 GHz band and uses a spread spectrum frequency-hopping scheme. It has 75 non-interfering channels that it uses for frequency hopping, which improves robustness against electromagnetic interference and also reduces radiated emission levels. The output power may be selected to be 10 mW or 100 mW as needed for the particular application. In Spring 2001, Sensoria expects to release an enhanced version of the WINS NG system that will include such features as:

- Increased sensing capability
- High resolution and high speed channels
- Addition of a DSP to enhance local diagnostics and prognostics
- Enhanced robustness and development environment with QNX RTOS (POSIX compliant)
- Improved network routing and throughput
- Enhanced processing capability
- Reduced size

This system will be designed for improved robustness and performance. The vision is to design for compatibility with future low cost ASIC architecture and lead to a high-volume commercial WINS solution.

4.3.2 PicoWINS

This is a much smaller, "chip-size" system that integrates sensor, processor, and transmitter on a single board. Components from the PicoWINS system are shown in Figure 4-3. With a reduced form factor, there is reduced processing capability relative to the NG systems. The prototypes for this system were developed under funding from DARPA as a feasibility study. The signal architecture supports multi-hop messaging so that data may be transmitted over greater distances as long as there are more PicoWINS nodes acting as repeaters along the way. Somewhere within the network one or more of the nodes communicates with a gateway that may be connected to the Internet. This allows access to databases for writing new data and for reading system configuration and operational parameters as well a historical data if required.

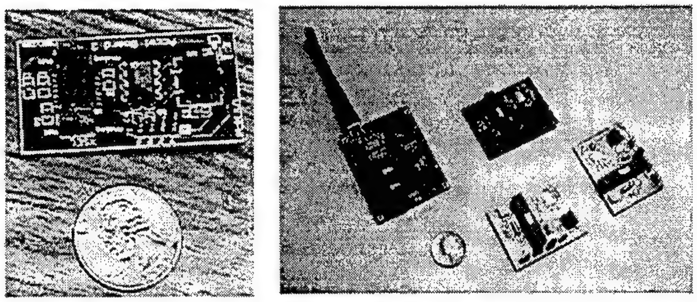

Figure 4-3: PicoWINS system components. (images: Sensoria, Inc.)

The PicoWINS nodes have been used in machinery diagnostic demonstrations for transmitting vibration, temperature, and other status information. The vibration data are used to then compute power spectral densities that may be used for diagnostic analysis. An illustration of a machinery monitoring setup is shown in Figure 4-4.

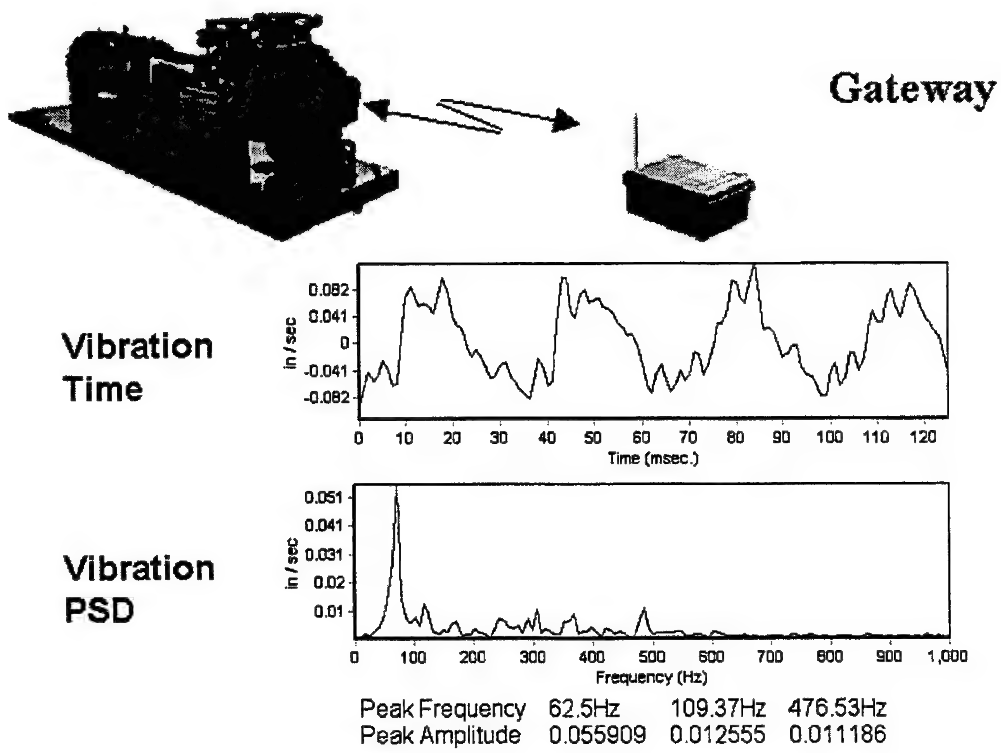

Figure 4-4: PicoWINS system as used for machinery diagnostics. The gateway retransmits the diagnostics signal to a data collection hub, which then interfaces with various signal monitoring and state condition estimators. (images: Sensoria, Inc.)

4.3.3 WINS Imager

This device is based on an architecture similar to that of the NG unit, but the Imager incorporates a digital camera. The system provides access to image capture at remote

locations. The trigger for capturing an image may be provided either remotely via the wireless link or on-site with an event trigger. The event trigger uses sensor input such as acoustic or seismic signals to detect a threshold shift and capture an image. Once the image is in local memory at the camera site, it may be transmitted via the wireless link to a central data collection site. Field operations at a range of 1.6 km have been demonstrated with images from this trial shown in Figure 4-5

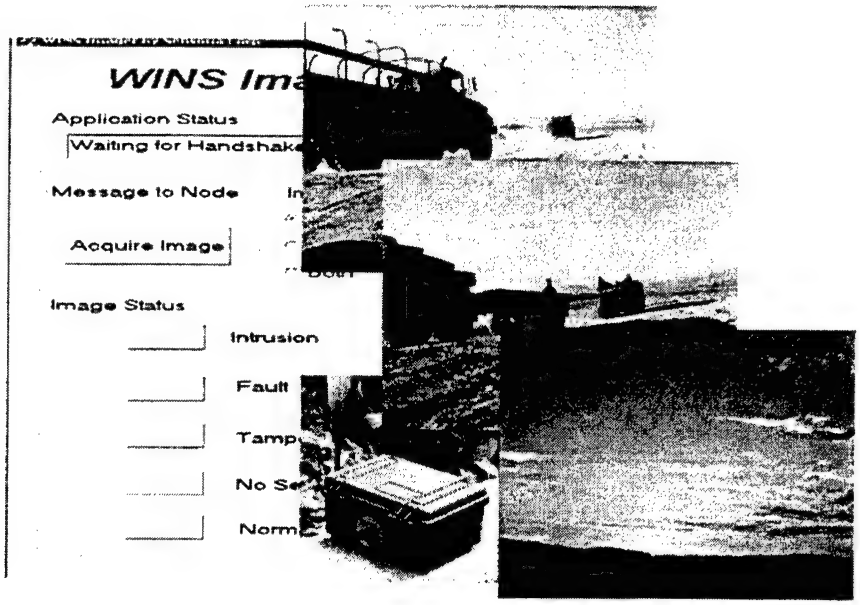

Figure 4-5: WINS Imager. Event trigger used to capture local activities. Transmit range in test was 1.6 km using commercial 900 MHz RF radio. The WINS Imager is at the bottom center with three captured images on the right. To the left is shown a screen shot of the WINS Imager Graphical User Interface. (images: Sensoria, Inc.)

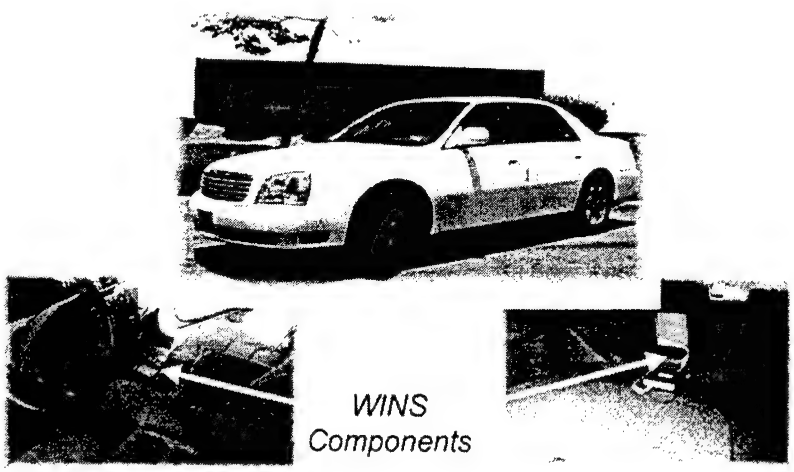

Figure 4-6: WINS Vehicle System. Prototype system installed on Cadillac and included various on board data sources including internal sensors, e.g., engine temperature, and external sensors, e.g., GPS. (images: Sensoria, Inc.)

4.3.4 WINS Vehicle Gateway

This system is intimately integrated with on-board vehicle systems for the purpose of improving maintenance and operational systems. The demonstration platform was selected to be a Cadillac automobile, which was instrumented with a wide variety of internal sensors, e.g., coolant temperature, intake air temperature, etc., and external sensors, e.g., GPS.

During routine operations, the WINS Vehicle System gathers data associated with the vehicle for later diagnostic and prognostic use. Upon interrogation at a service bay, the on-board data are communicated to a maintenance facility gateway via a 2.4 GHz RF link. The data are used locally to diagnose conditions on the automobile and also compared to database information that is available via the Internet for benchmark comparisons and trend analysis. An illustration of the overall system concept is shown in Figure 4-7.

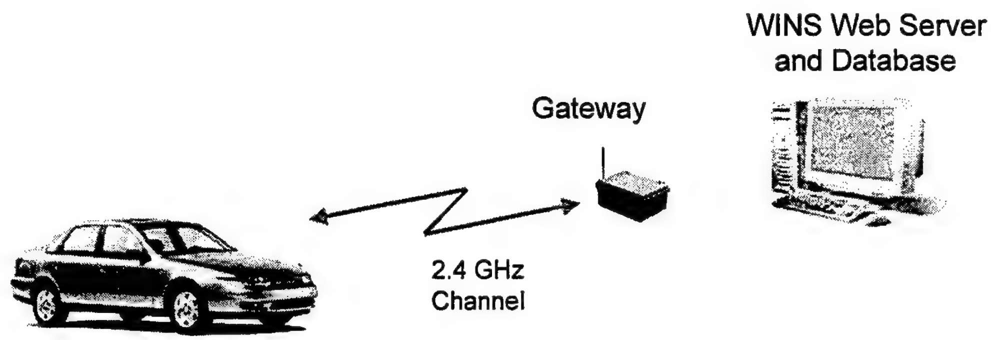

Figure 4-7: Vehicle data transmitted to service bay receiving station and interface to web server and database. Historical data from the database combined with current data from the vehicle provides for diagnostic and prognostic capability. (images: Sensoria, Inc.)

In addition to communication of data in the service bay, Sensoria has built the WINS system to be able to interact with web servers and data bases via the Global System for Mobile communication (GSM)[3] and the Personal Communications System (PCS).[4] By providing for GSM and PCS communication, vehicles on the road may transmit and receive data thus enabling opportunities for real-time operational data monitoring and processing.

4.4 Crossbow

Crossbow is a high-technology company that historically has focused on micro-electro-mechanical systems (MEMS) sensors. In October 2000, Crossbow announced the availability of a new sensor connectivity architecture called CrossNet. This system

[3] GSM (Global System for Mobile communications): A standard for how data is coded and transferred through the wireless spectrum. The European wireless standard also used in Asia, GSM is an alternative to CDMA. GSM digitizes and compresses data and sends it down a channel with two other streams of user data. The standard is based on time division multiple access. (from http://www.cio.com/archive/031501/speak.html)

[4] PCS (Personal Communications Services) An alternative to cellular, PCS works like cellular technology because it sends calls from transmitter to transmitter as a caller moves. But PCS uses its own network, not a cellular network, and offers fewer "blind spots"—areas in which access to calls is not available—than cellular. PCS transmitters are generally closer together than their cellular counterparts. (from http://www.cio.com/archive/031501/speak.html)

supports the delivery of data from both Crossbow sensors as well as generic sensors of a wide variety via their Smart Input/Output (SIO) module.

CrossNet is based on the Bluetooth radio protocol, which is developing as a widely embraced industry standard for short-range, high-bandwidth communication.

On October 16, 2000 Crossbow visited ADL to demonstrate their CrossNet wireless sensor node and Smart I/O input devices. Crossbow showed a system that had an accelerometer and a temperature coupled to the wireless node. Data were transmitted via a Bluetooth wireless link to a PC. The PC, loaded with a dedicated visualization program, called PC ComWare displayed the temperature and vibration data in quasi-real time. An example of the user interface for PC ComWare is shown in Figure 4-8. The only lag is the time to buffer, interrogate, and transmit the data.

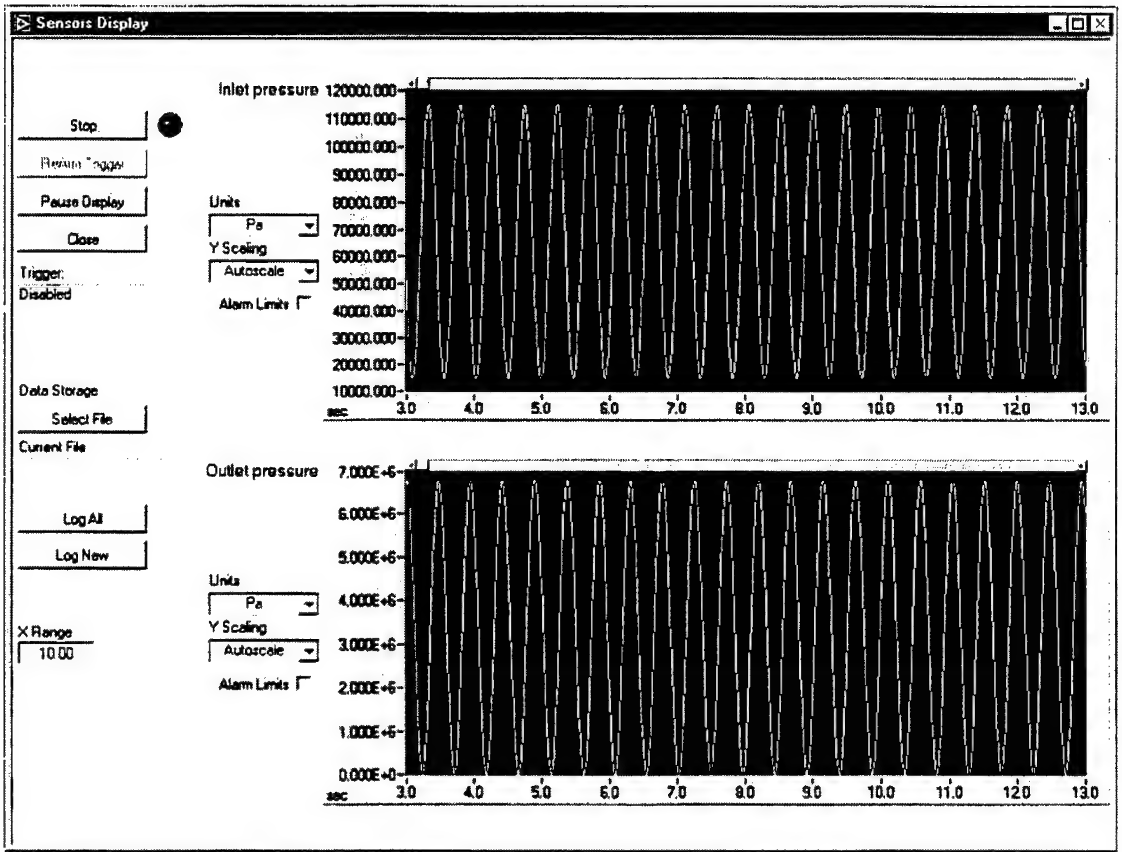

Figure 4-8: CrossNet Visualization Application

In addition, via the SmartCable program, the user is able to setup the wireless CrossNet nodes, interrogate the nodes for data, and, using PC ComWare, display the data on the users local system from many wireless sensors inputs. Each CrossNet node can accept up to four sensor inputs with a mix of sensed signals, e.g., temperature, pressure, acceleration, etc. The nodes use an IEEE 1451 interface to the sensors, which enables a sensor "plug and play" capability. The Transducer Electronic Data Sheet (TEDS) portion of the standard digitally characterizes the sensor, and the TEDS is integrated with the signal conditioning circuitry of the node, which then delivers data already converted to appropriate units for the sensor type. Sensor signals are interfaced to the node via a hardware component called the Smart Input/Output module (SIO). This

module contains the microcontroller logic necessary to convert the raw sensor signal to an IEEE 1451 compatible signal.

Figure 4-9 shows the CrossNet CN1000 node and a Smart I/O cable, which is used to connect sensors to the node. At present the CN1000 communicates wirelessly with a custom-built Bluetooth device that connects to the server's serial port. It is expected that this will be replaced in the near future with general-purpose Bluetooth PC cards.

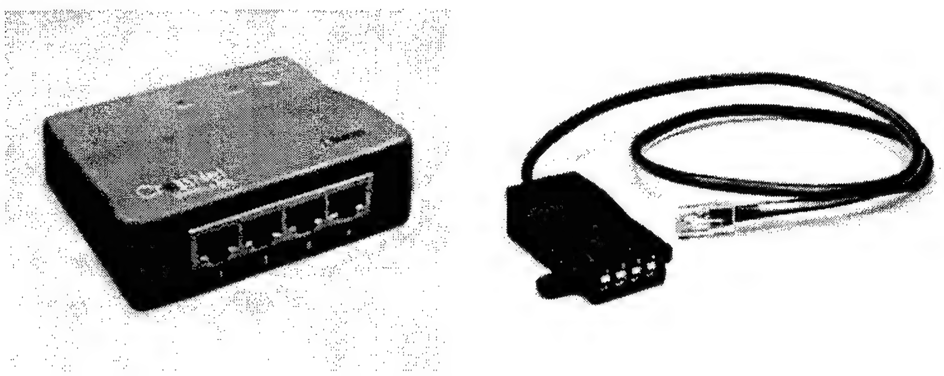

Figure 4-9: CrossNet Node and Smart I/O Cable

At present, the CrossNet nodes only gather input data from sensors. Next generation nodes are planned to include actuator output, which opens the door for local closed loop control at the node site with a selected status signal delivered back to a central facility via the wireless Bluetooth link.

Some specifics on the CrossNet node characteristics are as follows:

- Sensors: 4 sensors/node; self configuring, self identifying via IEEE 1451.2 TEDS
- Sampling rate: 100 Hz/sensor; higher rates available on OEM options
- Resolution: 16 bits
- Trigger: User defined window
- Data memory: 8k samples/sensor
- RF frequency: 2.4 GHz, unlicensed ISM band
- RF modulation: FHSS – Frequency Hopped Spread Spectrum
- Range: 10 m (0 dBm), 100 m (20 dBm) optional
- Size: 4"x3"x1"
- Programmability: Code stored in flash to support field upgrades

4.5 Intelemetric Systems

To illustrate the potential of using current wireless technologies to support condition-based monitoring of legacy aircraft, we have constructed a technology demonstrator based on the CrossNet system manufactured by Crossbow Technology, Inc. (see Section 4.4 above). This demonstrator helps to make concrete the reality of the opportunity offered by wireless sensing for legacy aircraft maintenance. The ideas behind the demonstrator have since become identified as Intelemetric™ Systems.[5] In building this demonstrator, our goals were to:

- Demonstrate the feasibility of using commercial wireless sensing hardware for data acquisition in a manner functionally similar to how it would be used for condition-based maintenance
- Develop a software package that could be used as a platform for advanced analysis applications such as predictive maintenance
- Demonstrate the feasibility and potential of making the data thus collected available over the Internet, to support a wide variety of user-specific tasks (e.g., maintenance scheduling and performance, deployment decision support, etc.)

Future implementations of operational wireless systems for legacy aircraft maintenance will differ in detail from the Intelemetric System implementation presented here. Nevertheless, the general framework and design guidelines for the Intelemetric implementation will prove a useful starting point for systems engineers considering such a development. In the following subsections we describe the design approach and implementation of the technology demonstrator.

4.5.1 Functional System Architecture

Figure 4-10 illustrates the functional architecture of the technology demonstrator. As shown, it consists of the following components:

- Representative **sensors** that are attached to a **CrossNet wireless node**, emulating the data acquisition device that would be installed onto a legacy aircraft
- **Node management software** that interfaces with the CrossNet node via a Bluetooth radio link, for periodic downloads of accumulated sensor data, and uploads of commands for modifying sampling rates, thresholds, etc.
- A **database server** that is used to aggregate the data stream generated by the remote sensing equipment
- **Server applications** that access the database and make the sensor data available to users who connect to the server via the Internet (or local-area Ethernet)
- **User client software** that is accessed via a conventional web browser, permitting the system operator to access and monitor the remote sensor data

[5] A white paper discussing the Intelemetric™ information architecture is available at www.intelemetric.com.

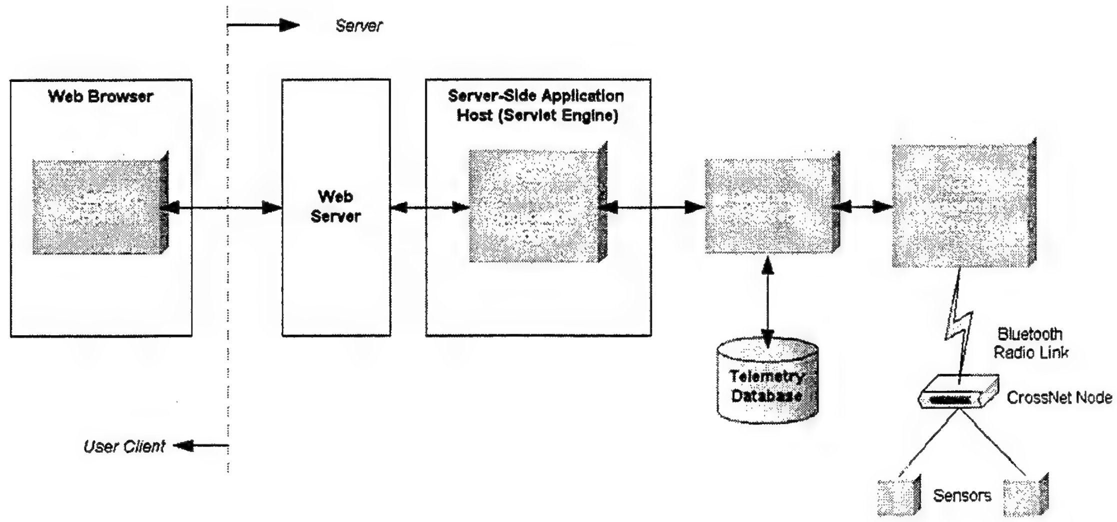

Figure 4-10: Functional Block Diagram of CrossNet-based Demonstrator

The Java programming language was selected for implementation of much of the server-side application logic and the user client software. The rationale for doing so is discussed in section 4.5.3 below.

4.5.2 Hardware Implementation

The first step in building the demonstrator was to determine what specific requirements it had to satisfy, and to identify suitable hardware that could meet these requirements. We first had to select which wireless sensor system (from the broad range of products surveyed in Chapter 3) to use as the backbone of the system. The following requirements were defined for this component of the demonstrator, with an eye towards the aircraft application that is the focus of this study:

- The communications protocol should be based on an **open** (rather than proprietary) **standard**, to facilitate interoperability with other systems downstream and minimize the risk of building a technological "walled garden"
- The system should have the capability to **store accumulated sensor data** on the remote device for periodic download, since it is likely that in practical application such downloads would only be performed between aircraft missions (e.g., when an aircraft taxis past a certain point in a hangar)
- The hardware should be compatible with a **wide variety of sensors**, to enable monitoring of a wide range of onboard systems and parameters (e.g., avionics health, weapons system status, structural loading, engine performance)
- The hardware's design should readily accommodate its **integration into Internet-oriented applications** to enable review by multiple, authorized users in potentially remote locations

Based on these considerations, we chose to use Crossbow Technology's CrossNet system, which uses the open Bluetooth protocol to make possible the rapid development and implementation of wireless monitoring systems. The demonstrator consists of conventional, low-cost sensors connected to a CrossNet node that transmits data wirelessly via Bluetooth. The data is received by an off-the-shelf PC also equipped with

a Bluetooth radio, which communicates the data over the Internet for remote monitoring, interpretation, and diagnosis. The benefits of using this technology include:

- Interoperability with other information systems based on the globally accepted Bluetooth wireless data transmission standard
- Scalable "plug and play" capability due to CrossNet node design
- Flexibility to accept a wide variety of sensors, including temperature, pressure, voltage, air and fluid flow, chemical, or vibration, thereby monitoring numerous types of onboard equipment
- Ease of integration into Internet-oriented applications via Crossbow's SoftSens application programming interface (API), which can be used to build custom applications that interface with a CrossNet node

The interface to the CrossNet hardware and all of the back-end functionality from Figure 4-10 (i.e., database server, web application server) is handled by an IBM Netfinity 3000 server, which is running the industry-standard Windows 2000 Professional operating system. The demonstrator's software (described further in 4.5.3 below) has been designed in a modular fashion so that the direct interface to the CrossNet nodes could be controlled from another PC, which must be linked to the server via the Internet or a local-area network (LAN) connection. The client software is accessed from a web browser on another PC running the Windows OS, whose only link to the server is an Ethernet connection via corporate LAN.

4.5.3 Software Implementation

The demonstration system illustrated in Figure 4-10 above contains four key software components:

- The user client software that is accessed by a remote user via a web browser
- The server-side application logic that acts as the "glue" between the client software and the sensor telemetry database
- The database server that aggregates the data stream generated by each sensor
- The node interface software that connects directly with the CrossNet node via Crossbow's SoftSens API

We describe the considerations that motivated our selection of development tools for each of these components in the following four subsections. We then describe the demonstration of the integrated system in section 4.5.4.

4.5.3.1 Client Software

A variety of tools and languages exist for developing the software that would be resident on an end-user's computer, enabling them to access and monitor the remote wireless sensor network. A thin-client design approach was contemplated for the implementation of this system component to minimize the requirements for time-consuming, custom software installations on any user's system (and to facilitate Internet-based demonstrations of system performance). A thin-client approach would also minimize problems associated with incompatible software revisions on different computer

systems. The following guidelines motivated the selection of the tools for client software development:

- It should easily integrate with the likely candidate for the server-side development tools
- It should be a mature, stable development environment with a large user base
- The tools should make possible a wide range of end-user functionality, from monitoring raw data in real-time to automatic condition-based alerting

After investigating a number of implementation options, we decided upon the Java platform for the implementation of the client software. Java offered the following advantages over other implementation options:

- Distributed
- Object-oriented
- Multi-threaded
- Network-centric
- Standard extensions for web integration

The client software was implemented as a Java applet, which is downloaded through a web browser interface. The functionality provided by this applet is to:

- Provide a visual representation of the topology (i.e., hubs, nodes, sensors) of a given sensor network
- Provide detailed information about each entity in a sensor network: operating uptime, performance parameters, thresholds, etc.
- Enable near-real-time monitoring of the raw output from a user-specified sensor, to demonstrate the feasibility of web-based access to wireless sensor data

Figure 4-11 presents a screenshot of one of the applet windows. The applet presents a Windows Explorer-like tree view of the topology of the connected sensor network on the left, presenting the hierarchy of known hubs, nodes, and sensors. This tree display allows the user to "drill down" to any component of the network to obtain more information about it. The right display panel presents more detailed information about whichever entity the user selects on the left. Currently it shows descriptive information about a CN1000 node that has been selected.

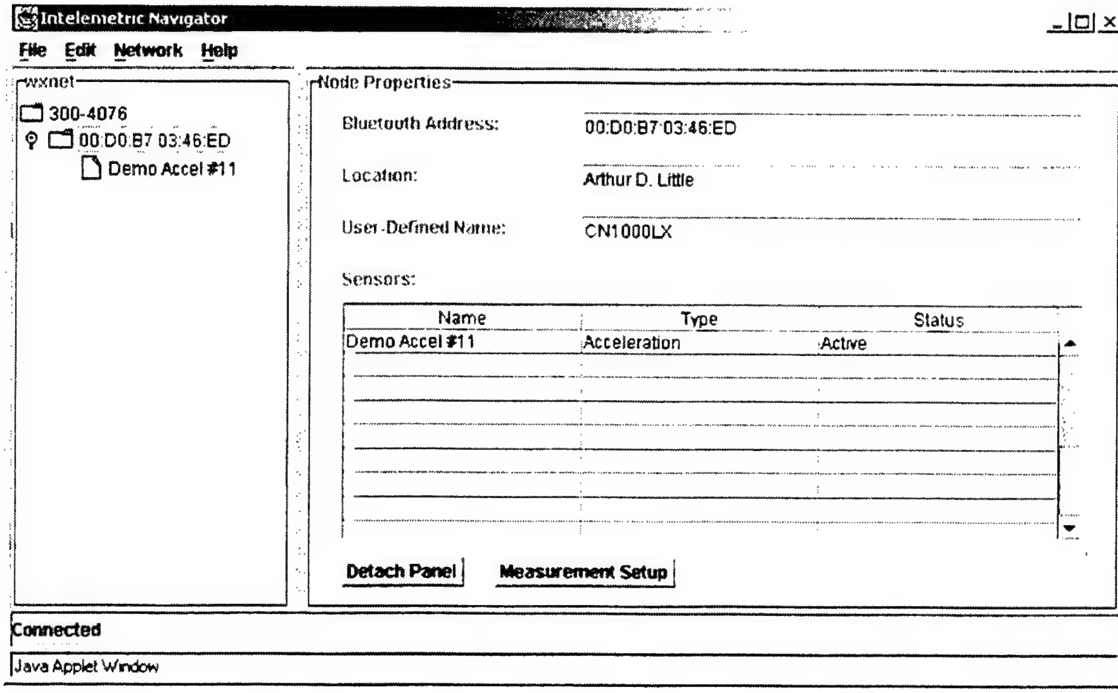

Figure 4-11: Screenshot of Java Client Software: Node Details

Figure 4-12 illustrates the information panel that is selected when the user selects a sensor from the tree display on the left. The display panel on the right provides detailed information about the sensor itself: the type of sensor (i.e., temperature, pressure, acceleration, etc.), its operating range, calibration dates, etc. The **Plot...** button at the bottom of the display allows the user to obtain a real-time (streaming or archived) plot of the sensor's output, an example of which is shown in Figure 4-13.

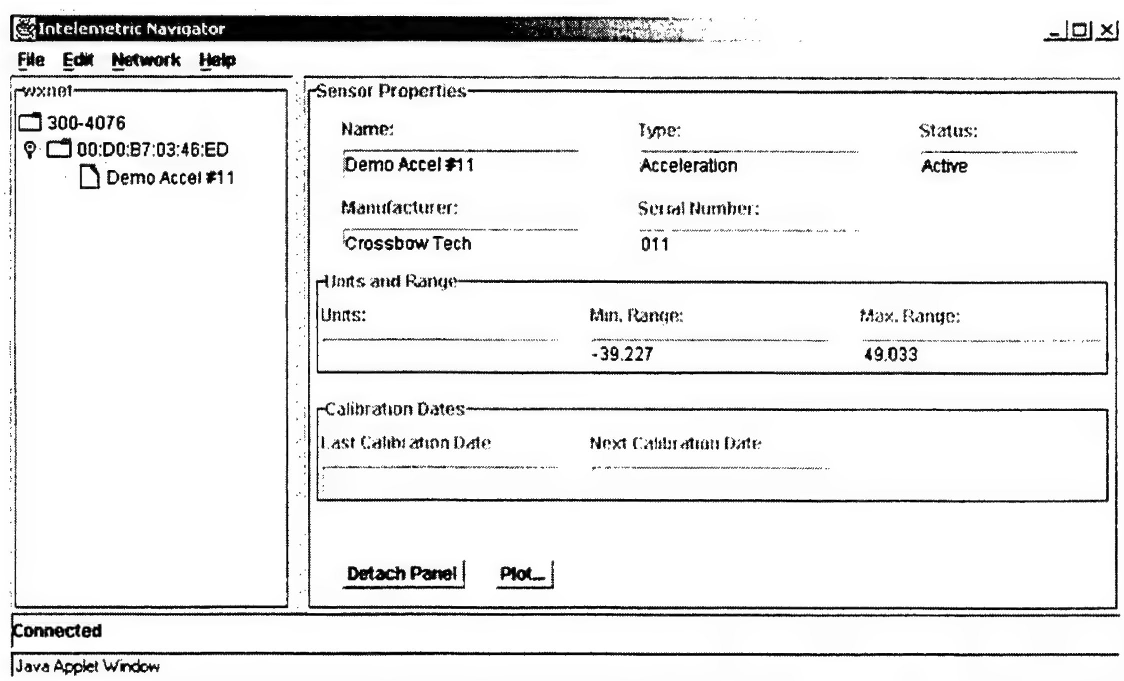

Figure 4-12: Screenshot of Java Client Software: Sensor Details

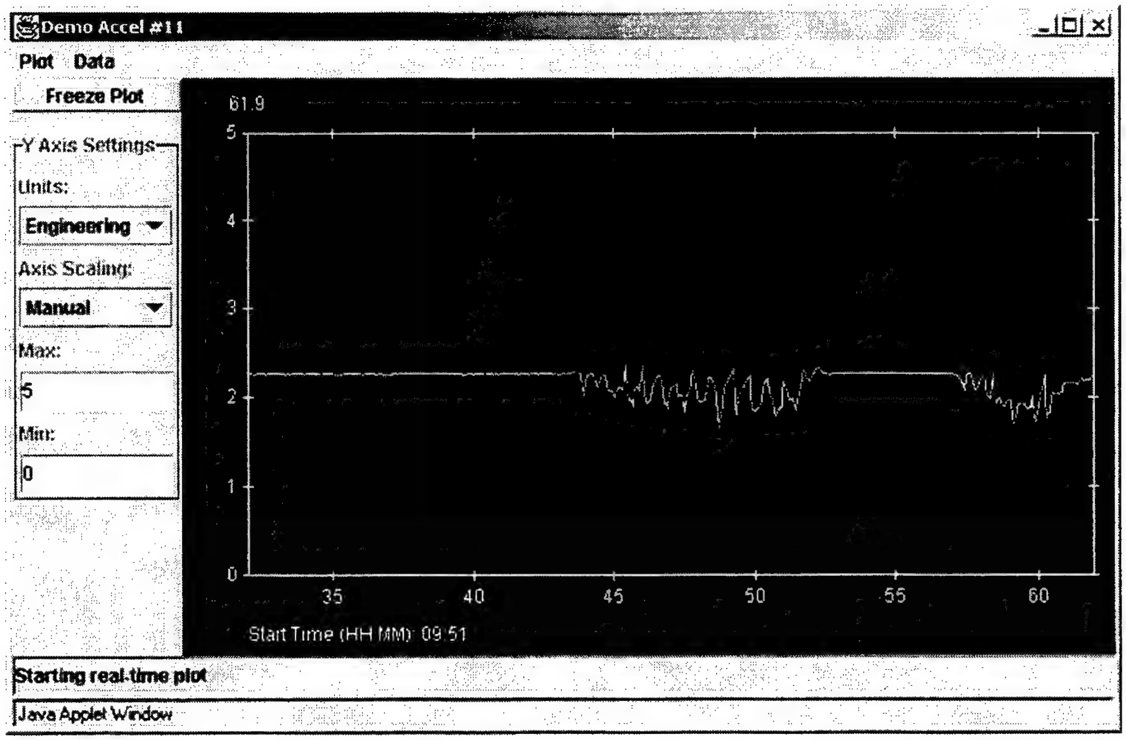

Figure 4-13: Screenshot of Java Client Software: Accelerometer Sensor Output

4.5.3.2 Server Application Logic

Given the network-centric nature of the demonstration system, it was necessary to select server development tools that would readily facilitate migration and installation in a web-based environment. The purpose of this application logic is to:

- Listen for connection requests to the server from web clients
- Accept connection requests from password-authorized clients
- Interface with the server-resident database that aggregates sensor network data
- Provide the web client (i.e., the Java applet) with an object-oriented description of a given sensor network
- Provide the web client with the data stream from a particular sensor upon request

For the same reasons that guided its selection as the client software development tools, Java was chosen as the implementation environment for the application logic resident on the server. It was also necessary to select a web application host that provides the runtime environment for the server-side Java logic. The JRun Servlet Engine from Allaire Corporation was selected for this task, based on its ease of use and previous development experience at ADL.

4.5.3.3 Database Server

A core component of the server-side software package is the telemetry database, which is read by the Java server applications interacting with the web client, and written to by the Node Interface Software described below. For this demonstrator, the following criteria were defined for selecting the database server:

- It should be an industry-standard database package that could be accessed by conventional means (i.e., the Standard Query Language, or SQL), to demonstrate the feasibility of building a technology platform that could easily be integrated with other enterprise information systems (e.g., data mining tools, logistics applications, etc.)
- It should be able to interface with clients (both read- and write-) resident on the same machine or over a network, for maximum flexibility of system configuration
- It should support the high data throughput that may be expected when the node interface software is streaming real-time data into the database, and multiple web clients are requesting real-time access to that data
- It should support the wide range of protocols in use for web application development (e.g., XML, Java, etc.) so that custom procedures and application-specific server logic can be added to the database easily (for example, automatic purging of obsolete data records, push or pull alerting functions, etc.)

Based on these considerations and previous ADL experience, we selected the Oracle 8i Enterprise Edition (v.8.1.5) database server for the demonstrator system. Oracle supports both classic relational (i.e., table-oriented) data representations, as well as object-oriented modeling, which may be particularly useful for characterizing the hierarchy of ad hoc sensor networks. It has been designed to support high-throughput transaction processing. Its client/server architecture makes it possible to install just the client software on remote data collection hubs, which can then interface with the database server over an Ethernet link. This provides for considerable flexibility in system configuration.

4.5.3.4 Node Interface Software

The Node Interface Software (NIS) is the piece of the system that communicates directly with the CrossNet CN1000 node via the Bluetooth link. It is a PC-based application built upon the SoftSens programming library developed by Crossbow Technology, Inc. The functions provided by this software are as follows:

- Connect with one or more CrossNet nodes and read a description of their attached sensors
- Deposit the description of the sensor network into a database that may be resident on the same machine as the NIS or accessed via the Internet or a LAN
- Manage the data acquisition parameters of each connected sensor node
- Perform streaming or batch "dumps" of raw sensor data into the database

Crossbow has designed the SoftSens library so that it can be used from within the Visual Basic, Visual C++, or LabView development environments on the Windows operating system. In the interest of rapid application development for this demonstration, Visual Basic was selected for development of the NIS. Figure 4-14 presents a screenshot of the NIS.

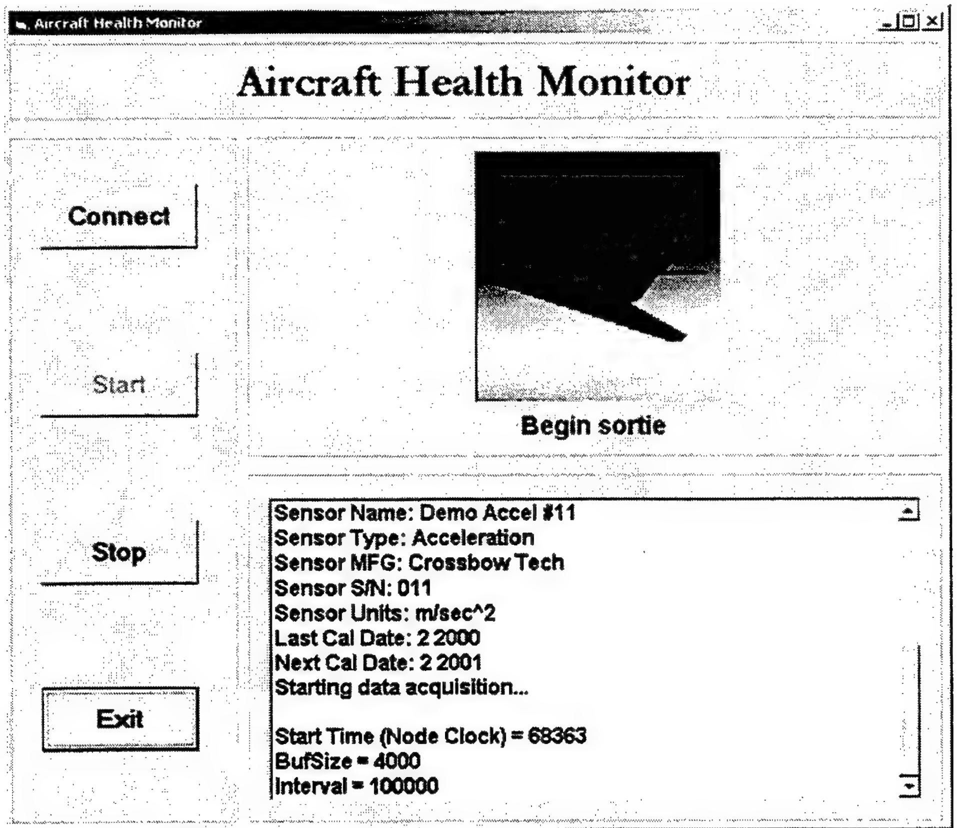

Figure 4-14: Screenshot of Node Interface Software for Batch Data Downloads

4.5.4 Demonstration Results

The integrated demonstration system was presented to a select group of Arthur D. Little clients at an industry workshop held on January 30, 2001. The purpose of this workshop was to identify market interest and direction in the area of wireless, Internet-enabled monitoring and control systems. The following capabilities were demonstrated at this workshop:

- Plug-and-play, command-and-control software structure that makes it possible to vector real-time wireless sensor data into an Oracle database
- Near-real-time access to the wireless sensor data via an Internet connection and simple web client

Following this demonstration, an upgrade was made to the client software to make it possible for the user to select which mode of data visualization they prefer: 1) near-real-time streaming output that is synchronized to a sensor; or 2) review of complete "historical" archive of sensor data stored in the database. In practical application, the former might be preferred during interactive maintenance operations, while the latter would most likely be used as input into predictive maintenance or diagnosis algorithms.

5. Technology Patents

5.1 Follow-up Evaluation

Subsequent to the QFD analysis discussed in Section 3, Raytheon and The Aerospace Corporation were contacted to gather more information about the selected patents. Two questions were posed to both companies:

1. Are the patents available for licensing to the Air Force and, if so, are they available on a royalty free basis?

2. Has the technology been reduced to practice and, if so, what is the level of concept maturity?

5.2 Raytheon

Two of the three Raytheon patents are based on similar technology, and are still owned by Raytheon. The patents are:

- US #6,009,356: "Wireless transducer data capture and retrieval system for aircraft" Patent issued to Raytheon on December 28, 1999. The patent addresses a safety and surveillance recorder system for aircraft that incorporates wireless sensors to monitor critical components and operational characteristics of an aircraft. (See Section 3.4.1 for further description.)

- US #5,798,458: "Acoustic catastrophic event detection and data capture and retrieval system for aircraft" Patent issued to Raytheon on August 25, 1998. It addresses an acoustic sensor system for detecting failures in aircraft in the event of a catastrophic event. (See Section 3.4.1 for further description.)

Raytheon still owns these patents, but the inventor no longer works for Raytheon. ADL was unable to contact the inventor and we were not able to gain an understanding of the level of maturity of the technology.

The third Raytheon patent is:

- US #5,809,220: "Fault tolerant distributed control system" Patent issued to Raytheon on September 15, 1998. The patent covers a fault tolerant distributed intelligent control system for sensing and actuation via a fiber optic communication media interconnecting two or more intelligent nodes. (See Section 3.4.1 for further description.)

This patent has been sold to CBL Systems as part of a Raytheon spin-off. CBL, formally Raytheon Control-by-Light, was established to develop new fiber optic technology applications that could serve as an alternative or complement to conventional networking media. CBL markets include commercial building automation,

security/access and fire alarms, as well as transportation and aircraft control systems. There is a possibility that CBL may be willing to license the technology to the Air Force, but its availability was not confirmed.

A Business Wire press release was issued on June 22, 2000 entitled "CBL Systems Corporation Completes Acquisition of Raytheon Company Fiber-Optic Solutions Business Unit."[6] For further information, contact CBL Systems, 25 South Street Hopkinton, Massachusetts 01748. On-line information is also available at www.control-by-light.com.

5.3 The Aerospace Corporation

The QFD down-select process identified one patent of interest from The Aerospace Corporation. The patent was:

- US #5,982,297: "Ultrasonic data communication system" Patent issued to The Aerospace Corporation on November 9, 1999. It describes an ultrasonic data communications system that allows bi-directional transfer of data through a coupling medium without the use of electrical power wires for controlling embedded sensors and actuators. (See Section 3.4.1 for further description.)

The Intellectual Property Licensing office at The Aerospace Corporation directed us to speak directly with the inventor, Dr. Richard Welle, for answers to our questions. Welle advised that development work underlying the patented technology was funded by the US government and, as a result, was available to the Air Force royalty free.

Further discussions revealed that Welle has demonstrated the fundamental technology in the laboratory at The Aerospace Corporation. Their work was related to spacecraft, but he was very interested in applying it to aircraft as well. The technology is based on the concept of transmitting power ultrasonically from a central power station to one or more power receiving stations distributed on a structure. The transmission medium is the structure itself. Welle has demonstrated the ability to transmit usable power levels (10-100 mW) at 100 kHz in the laboratory. The patent covers power transmission and also data communication over the same channel by modulating the carrier frequency used to transmit the power. Further development is needed to make this a viable technology. It does have, however, the virtue that remote sensor pods can be completely autonomous with no need for local power.

[6] This press release is available at www.businesswire.com/webbox/bw.062200/201742466.htm.

6 Conclusions and Recommendations

6.1 Comments

The state of technology for wireless sensors is advancing in lock step with advances in processor and telecommunication technology. There are a wide variety of systems available, but the marketplace is constantly changing with companies leap-frogging each other in terms of product functionality. This report should be considered a snapshot of the state of the industry at this time. Even during the course of the study, new developments were taking place. To the extent possible, these developments have been incorporated into this report to update earlier presentations made to AFRL.

Based on our findings we offer the following conclusions and recommendations for moving ahead.

6.2 Conclusions

- Commercial wireless sensors components and communications infrastructure are mature enough to begin developing systems.

- Wireless systems are available with communication channels based on RF, ultrasonic, IR, and laser modalities.

- The most popular RF bands are 2.4 GHz (Bluetooth) and 900 MHz (cordless phone).

- A high-level systems development approach is required to capture the full potential of wireless sensors for aircraft maintenance application.

- System designs that respond to specific Air Force maintenance activity needs are required, and these designs can be developed from existing hardware solutions.

- Integration of the wireless sensor components requires a carefully designed information architecture, and tools for doing this are not available from a single source.

6.3 Recommendations

ADL recommends that the AFRL commission a multi-pronged effort focused on leveraging the growing capability offered through wireless sensors. The recommended tasks and their objectives are as follows:

- Commission a study to identify specific maintenance needs that are not being currently met and determine the value of meeting the stated maintenance requirements, i.e., Who saves how much?

- Develop a system architecture and a subsystem design to meet the identified needs through use of available sensors, algorithms, etc. and demonstrate feasibility of the system in a laboratory test.

- Select a suitable pilot study for implementation in actual aircraft with communication to ground-based systems. The pilot study should be sufficiently limited in scale to keep costs at reasonable levels but sufficiently large in scale to demonstrate the utility of the approach. Presuming success of the pilot study, follow on activities would be required to evaluate the cost/benefit of such a system and to plan wider scale implementation.

In conjunction with this initiative, ADL recommends that AFRL be aware of and follow related areas including:

- Being proactive in incorporating wireless sensor products into existing and new maintenance systems; Sensoria WINS and Crossbow CrossNet systems offer promising system components.

- Harvesting the rich body of information on maintenance diagnostics and prognostics and incorporating this information into any system development for aircraft maintenance.

- Integrating the maintenance algorithms with wireless sensor systems for quasi-real time visibility into the state of the aircraft.

Appendix A: Related Areas to Watch

A.1 Artificial Intelligence (AI) Based Data Processing

Of particular note to watch is Orincon Industries. On-line information is available at www.orincon.com. Oricon offers

- Software tools and solutions for AI signal processing
- Data fusion, data mining, signal processing, neural nets, advanced decision aids
- Real-time Interactive Programming and Processing Environment (RIPPEN®), a proprietary graphical programming environment for the design, prototyping, implementation, test, and operation of a range of applications in signal and image processing and information analysis

A.2 Condition-Based Maintenance

A large body of literature and considerable interest has been developed over the years in condition-based maintenance (CBM). It has been long recognized that preventive maintenance has a high cost associated with both the process itself as well as the incidental cost associated with accidentally introducing faults during the PM procedure.

CBM is a methodology whereby systems are not broken down until such an action is indicated by objective measures. This is codification of the adage "If it ain't broke, don't fix it."

A window into this enormous field is available via on-line resources at:

- The National Institute of Standards and Technology "Five to Ten Year Vision for Condition-Based Maintenance" by John S. Mitchell at http://atp.nist.gov/www/cbm/mitchell/mitchndx.htm
- NIST ATP program on CBM at www.atp.nist.gov/www/cbm/cbm_off.htm
- CTRL Systems, Inc., Ultrasound Condition Based Monitoring at www.ctrlsys.com
- Ames Research Center, CBM for the ARC Wind Tunnel Facilities at http://ic-www.arc.nasa.gov/ic/projects/condition-based-maintenance
- CBM at the Applied Research Laboratory at Penn State at www.arl.psu.edu/areas/soa/conditionmaint.html
- and many others

A.3 Oak Ridge Wireless Initiative

Quoting the Oak Ridge National Laboratory site "The wireless initiative program at Oak Ridge is committed to a seamless integrated solution for creating a complete intelligent measurement and control wireless infrastructure (IMACWIN) applicable to industry, as well as, military sectors through partnerships with industry, academic institutions, and government agencies. The vision focuses on technological issues to develop a network topology with an architecture transparent to hardware origin and with performance capable of meeting the agility demanded by future economic challenges and growth." For further information see www.ornl.gov or contact Wayne W. Manges at mangesww@ornl.gov.

A.4 Lawrence Livermore National Laboratory Sensors Development

LLNL has an extensive sensors development program including such areas as optical chemical sensors, solid-state cameras, radiation sensors, tomography systems for detecting defects and corrosion, exhaust control sensors, 3D surface imaging sensors, MEMS fiber optic pressure sensor, miniature gas chromatography sensor, and much more. For further information see www.llnl.gov/sensor_technology/SensorTech_contents.html.

A.5 Bluetooth Wireless Protocol

Bluetooth is becoming a *de facto* industry standard for short-range communication. It will enable integration of sensors with inexpensive wireless networks in a number of application areas. The original consortium members included Motorola, Ericsson, Nokia, Intel, IBM, 3Com, Lucent, and Toshiba. Since the beginning in 1994, the Bluetooth consortium has grown to over 2000 companies, an indication of just how much the technology has captured the interest of manufacturers. The RF communication is based on spread spectrum modulation with a 2.4 GHz unlicensed carrier and operates over ranges not more that 100 m, though the nominal range is 10 m for the initial systems. Effective data rates of 721 kbits per second are supported within point-to-point and point-to-multipoint network architectures. Further information is available at www.bluetooth.com.

Appendix B: Brainstorming Session

B.1 Overview

The charter of the brainstorming session was to remove limiting blinders and consider technologies beyond wireless sensors for maintenance diagnostics and prognostics. In the spirit of brainstorming sessions, no judgments were made; only a stream of concepts was developed. Subsequent analysis of the brainstormed ideas would be needed to evaluate these ideas and quantify various technical, business, and human factors.

B.2 Sensor Concepts

- Photonics - fiber optic sensors
- Bearing noise and vibration
- Crack propagation
- Fiber coating to enhance sensitivity to desired signal

B.3 Time Domain Reflectometry (TDR)

- Optical TDR in fibers for distributed sensing
- Acoustical TDR in structural elements
- Electrical TDR in structural elements

B.4 Acoustics and Vibrations

- Acoustic emissions for structural monitoring
- Vibration spectral analysis for engine evaluation

B.5 Coatings

- Bio-reactive coatings
- Visually identified response to thermal, pH, integrated time/temperature
- Use NDE to determine condition of coatings
- Design of experiments to predict long term environmental effects

- Install sample sites for monitoring corrosion

B.6 Electrical

- Capacitance between adjacent cabling for insulation or cable degradation
- AC impedance measurements for corrosion
- Capacitance measurements for corrosion
- Piggy-back high frequency interrogation signals on existing wires

B.7 Chemical

- "Artificial nose" for burning insulation
- Evolved gasses or combustion products for excessive heating in electronics
- Detection of off-gassing from electrical, thermal, frictional failures
- Ion detection for early combustion

B.8 Magnetic

- Crack induced magnetic anomalies; eddy currents

B.9 Electromagnetic

- Radar stroboscope for imaging turbine blades

B.10 Signal processing

- Improved signal analysis in ground support equipment
- Signal conditioning, pulse shape, timing
- Fingerprinting as is done in cell phone identification
- Model-based signal processing and analysis
- Neural nets